Proceedings of the
Workshop on

"Goals and Technologies for Tomorrow's Gas Turbines"

hosted by

College of Engineering
Georgia Institute of Technology
Atlanta, GA 30332
June 15-16, 1998

as part of
Army Research Office MURI
on
Intelligent Turbine Engines

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13. ABSTRACT *(Maximum 200 words)*

The objective of this program is to investigate control approaches for improving the performance of gas turbine engines, with special emphasis on gas turbine compressors and combustors.

The presentations at the workshop were delivered by leading experts from government, industry and universities. The objectives of these presentations and the discussions were to bring into better focus: (1) Problems that adversely affect the performance and cost of operation of gas turbines; and (2) Present and future technologies, especially control approaches, that could significantly improve aircraft performance and reduce their life cycle cost.

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Preface

This document contains copies of the presentations at the workshop on **Goals and Technologies for Future Gas Turbine Engines** that was held on the Georgia Tech campus during June 15-16, 1998. This workshop was organized as part of **Georgia Tech's University Research Initiative on Intelligent Turbine Engines** that is supported by the Army Research Office. The objective of this program is to investigate control approaches for improving the performance of gas turbine engines, with special emphasis on gas turbine compressors and combustors .

The presentations at the workshop were delivered by leading experts from government, industry and universities. The objectives of these presentations and the discussions were to bring into better focus: 1) Problems that adversely affect the performance and cost of operation of gas turbines; and 2) Present and future technologies, especially control approaches, that could significantly improve aircraft performance and reduce their life cycle cost.

The talks appear in this report in the order in which they were presented. The workshop itself consisted of four sessions and an Open Forum (see following workshop program). The four sessions covered the following topics: 1) Future Gas Turbines Needs, 2) Control of Compressors Performance, 3) Combustors Design and Control, and 4) Enabling Technologies. The report closes with presentations by Drs. Sturgess and Mularz, which was part of the Open Forum.

We would like to take this opportunity to thank the Army Research Office for providing the resources needed to organize this workshop. Also, we wish to thank the speakers and session chairs for taking time off from their busy schedules to participate in the workshop and for providing us with copies of their talks for inclusion in this report.

In closing, it is our hope that this report will serve as a bench mark of the state of the art of active control of gas turbines' compressors and combustors performance in 1998.

Ben T. Zinn
Aerospace and Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia

David Dr. David M. Mann
Associate Director, Engineering Sciences Division
Army Research Office
Durham, North Carolina

Program for Workshop on
Goals and Technologies for Tomorrow's Gas Turbines
At the
Manufacturing Center Auditorium on the Georgia Tech campus

Sponsored by
Army Research Office and the Georgia Institute of Technology
Atlanta, Georgia
June 15-16, 1998

Monday, June 15, 1998

Session I: Future Gas Turbines Needs - Dr. David Mann, Associate Director, Engineering, ARO, Session Chair

8:30 a.m.	Dr. Jean Lou Chameau, Dean, College of Engineering, Ga. Tech - **Welcoming Comments**
8:45 a.m.	Dr. David Mann, Associate Director, Engineering Sciences Dept., Army Research Office - **Active Combustion Control - A Key Element in the Strategy for the Fuel Efficient Army After Next**
9:00 a.m.	**Dr. B. T. Zinn, Aerospace Engineering, Ga. Tech** - Georgia Tech – Georgia Tech's Intelligent Turbine Engine Program
9:15 a.m.	Mr. Richard E. Quigley, Deputy Director, AFRL/PR, WPAFB - **The IHPTET Program**
9:45 a.m.	Coffee Break
10:15 a.m.	Mr. Harvey Maclin, Manager, Advanced Military Engines Technology, GE Aircraft Engines - **Aircraft Propulsion Systems Today and Tomorrow**
10:45 a.m.	Mr. Lee L. Coons, Vice President Engineering, Pratt & Whitney - **Impact of Modeling and Diagnostic Technologies on the Operating Cost of Aircraft Gas Turbine Engines**
11:15 a.m.	Dr. Robert Fagan, Chief, Compression Systems, Allied Signal Engines – **Technology Challenges for 21st Century Gas Turbines**
11:45 a.m.	Dr. John Meier, Director, Products Definition & Technical Development, Allied Signal Engines – **Challenges of Advanced Technology in Military Applications**
12:15 p.m.	**Lunch will be served next to the auditorium**

Session II: Control of Compressors Performance - Dr. Louis A. Povinelli, Chief Scientist, Propulsion, NASA Lewis, Session Chair

1:15 p.m.	Dr. Om Sharma, Senior Fellow, Pratt & Whitney - **Resonant Stress, Flutter and Stability Challenges in Aircraft Gas Turbine Engines**
1:45 p.m.	Dr. Richard Murray, Professor, Dept. of Mechanical Engineering, CalTech - **Bifurcation Control of Compression Systems Using Pulsed Air Injection**
2:15 p.m.	Dr. Tony Strazisar, Senior Technologist, NASA Lewis - **The NASA-Lewis Compression System Stability Program**
2:45 p.m.	Dr. Yedidia Neumeier, Senior Research Engineer, Aerospace Engineering, Ga. Tech - **Passive and Active Control of Stall in Axial Compressors**
3:15 p.m.	Coffee Break

Session III: Combustors Design and Control - Dr. Mel Roquemore, Senior Scientist, Air Force Laboratory, Propulsion Division, AFRL/Propulsion Directorate Session Chair

3:30 p.m.	Dr. Hukam Mongia, Manager, Combustion Technology, GE Aircraft Engines fi **Low-Emissions Combustors; Design and Analysis Tools**
4:00 p.m.	Dr. Daniel E. Sokolowski, NASA Aeropropulsion Liaison and IHPTET Focal Point, NASA Lewis - **A Revolutionary Combustor Front-End Design Concept**
4:30 p.m.	Dr. Ben T. Zinn, Professor, Aerospace Engineering, Ga. Tech - **Active Control of Combustion Instabilities**
5:00 p.m.	Dr. Kenneth H. Yu, Physical Scientist, Naval Air Warfare Center fi **Active Combustion Control Using Pulsed Fuel Injection**
6:00 p.m.	Reception - **President's Suite- Georgia Tech's Success Center**

Tuesday, June 16, 1998

Session IV: Enabling Technologies - Dr. Marc Jacobs, AFOSR, and Dr. Linda Bushnell, ARO, Session Co-Chairs

8:30 p.m.	Mr. Stephen Przybylko, Aerospace Engineer, WPAFB - **Active Control Technologies for Aircraft Engines**
9:00 a.m.	Dr. Ari Glezer, Professor, Mechanical Engineering, Ga. Tech - **Mixing Control Using Synthetic Jets**
9:30 a.m.	Dr. Mark Allen, Professor, Electrical & Computing Engineering, Ga. Tech – **High Temperature Wireless Sensors**
10:00 a.m.	**Coffee Break**
10:30 a.m.	Dr. Ronald K. Hanson, Professor and Head, Mechanical Engineering, Stanford University - **Diode Laser Absorption Sensors for Combustion Monitoring and Control**
11:00 a.m.	Dr. Wassim Haddad, Professor, Aerospace Engineering, GA Tech - **Nonlinear Robust Controller Synthesis for Jet Engine Compression Systems**
11:30 a.m.	Dr. Sanjay Garg, Acting Chief, Controls & Dynamics, NASA Lewis - **Active Combustion Control for Future Aircraft Engines**
12:00 p.m.	**Lunch will be served next to the auditorium**

Session V: Panel Discussion and Laboratories Tour

1:00 p.m.	**Open Forum - Future Trends in Gas Turbines Systems,** Session Moderator: Dr. Geoff Sturgess, Vice President, Engineering, Innovative Scientific Solutions, Inc.
	Dr. Edward J. Mularz, Chief, Engine Components Div., US Army Research Laboratory – **Research Needs for Future Gas Turbines – a U.S. Army Perspective**
3:00 p.m.	Coffee Break
3:30-5:00 p.m.	Visits to Ga. Tech's **Compressor, Combustion, Fluid Mechanics** and **MEMS** Laboratories

Workshop Proceedings

"Goals and Technologies for Tomorrow's Gas Turbines"

Contents of Presentations

13) "Revolutionary Combustor Front-End Design Concept"
Dr. Daniel e. Sokolowski, NASA Aeropropulsion Liaison & IHPTET, NASA-Lewis

14) "Active Control of Combustion Instabilities"
Dr. Ben T. Zinn, School of Aerospace Engineering, Georgia Institute of Technology

15) "Active Combustion Control Using Pulsed Fuel Injection"
Dr. Kenneth H. Yu, Physical Scientist, Naval Air Warfare Center

16) "Active Control Technologies for Aircraft Engines"
Stephen J. Przybylko, Aerospace Engineer, Turbine Engine Division, AFRL

17) "Mixing Control Using Synthetic Jets"
Dr. Ari Glezer, Professor, Mechanical Engineering, Georgia Institute of Technology

18) "MEMS Devices for High Temperature Applications"
Dr. Mark G. Allen, Professor, Electrical & Computer Eng., Georgia Institute of Technology

19) "Diode-Laser Absorption Sensors for Combustion Monitoring and Control"
Dr. Robert K. Hanson, Professor and Head, ME, Stanford University

20) "Nonlinear Robust Controller Synthesis for Jet Engine Compression Systems"
Dr. Wassim M. Haddad, Professor, Aerospace Eng., Georgia Institute of Technology

21) "Active Combustion Control for Future Aircraft Engines"
Dr. Sanjay Garg, Acting Chief, Controls & Dynamics, NASA-Lewis

22) "Future Trends in Gas Turbine Systems"
Dr. Geoffrey J. Sturgess, VP, Engineering, Innovative Scientific Solutions (ISSI)

23) "Research Needs for Future Gas Turbines – a US Army Perspective"
Dr. Edward J. Mularz, Propulsion Directorate, Vehicle Technology Center,
ARL, NASA-Lewis

ACTIVE COMBUSTION CONTROL

A Key Strategy for the Fuel Efficient Army After Next

DR. DAVID MANN
ACTING DIRECTOR
ENGINEERING DIRECTORATE
US ARMY RESEARCH OFFICE

WORKSHOP ON
Goals and Technologies for Tomorrow's Gas Turbines
Georgia Institute of Technology
15 June 1998

PRESENTATION OUTLINE

Fuel Efficient Army After Next (ARL/ARO/TACOM)

- Study overview
- Conclusions

Research for Future Combat Vehicle Propulsion

- Blue Ribbon Panel Recommnendations

Intelligent Engine Research Thrusts

- Active Engine Control
- "Intelligent Turbine Engine"

FUEL EFFICIENT AAN
Structure of Study

WHITE PAPER

FUEL EFFICIENT AAN

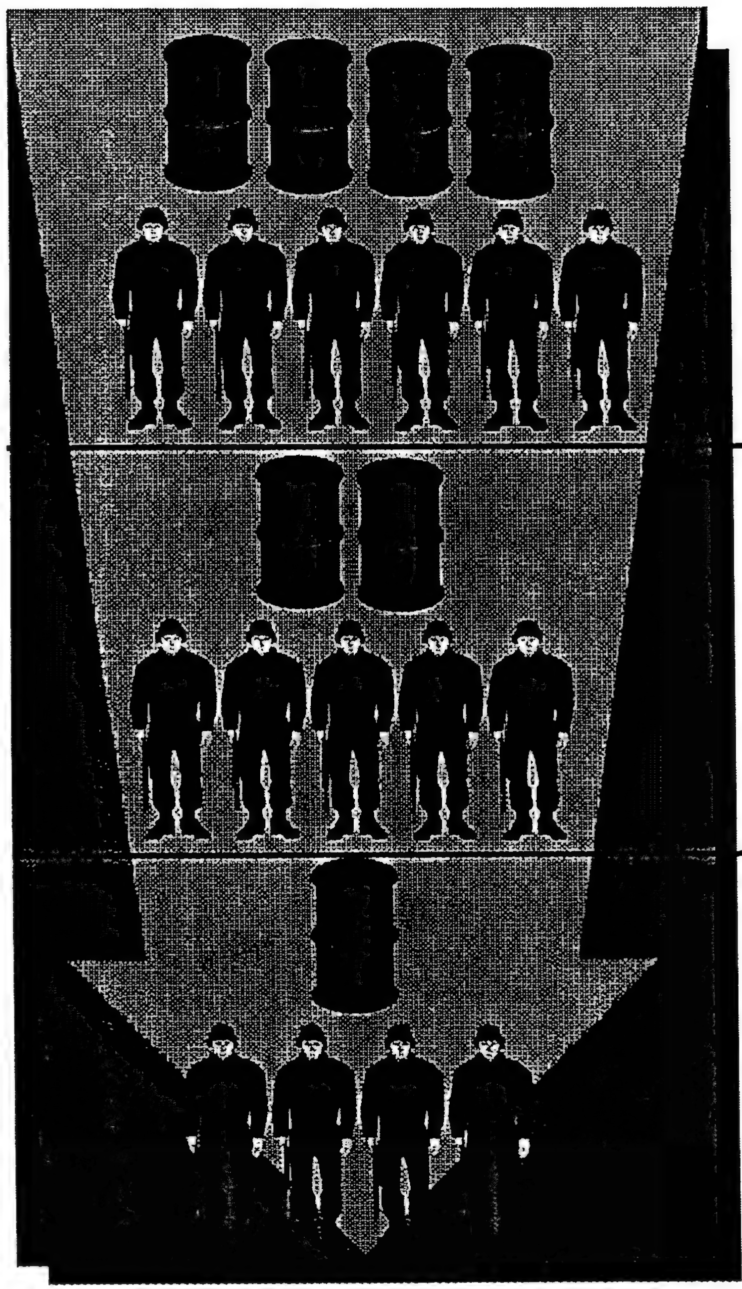
I. Introduction
- Motivation
- Basic thesis

II. Analysis and results
- S&T investment costs
- Implementation costs
- Need for Army initiative and leadership role
- Fuel usage analysis

III. Major technical thrust areas
- Impact and synergies
- Technical nuggets

IV. Program plan
- Scope
- Structure

V. Conclusions and recommendations



FUEL EFFICIENT AAN
THE PATH TO FUEL EFFICIENCY

BASELINE FUEL AND INFRASTRUCTURE

50% IMPROVEMENT IN PROPULSION EFFICIENCY

- ENGINE EFFICIENCY
- POWER TRANSMISSION
- ENERGY STORAGE

50% REDUCTION IN PROPULSION POWER REQUIREMENT

- PLATFORM WEIGHT
- PROPULSIVE EFFICIENCY

FUEL EFFICIENT AAN INITIATIVE

FIVE TECHNOLOGY THRUSTS

[redacted]

Engines/prime movers
Power transmission
Energy storage

[redacted]

Lightweight platform structures
Advanced materials

[redacted]

Composite technology
Active protection systems

[redacted]

Tiltrotors & advanced air platforms
Propulsors (tracks, wheels, rotors)
Advanced UAV/UGV concepts

[redacted]

Tactical routing
Field housing/support

ARMY FUEL EFFICIENCY STRATEGY

NEAR TERM

TECHNOLOGY INSERTION INTO FIELDED SYSTEMS (T700, AGT1500)

- **10% Fuel Consumption Reduction through insertion of existing material technology and available components.**
- **Cost for Implementation: $100M**
- **Timeframe: 5 Years**

MID TERM

INTRODUCE T800, LV100, AND MODERN TECHNOLOGY DIESELS INTO THE FIELD

- **25% Fuel Consumption Reduction through accelerated Tech Base, TD/ATD, and Engineering Development programs. Key areas include advanced coatings, high temperature materials, and light weight composites.**
- **Cost for Development, Implementation, and Fielding: $900M**
- **Timeframe: 10 Years**

FAR TERM

ADVANCED CONCEPTS FOR ARMY AFTER NEXT

- **75% Fuel Consumption Reduction through full gamut of system concept studies, advanced propulsion and structural designs, and component improvements.**
- **Phased technology demonstrations and full scale development leading to fielding**
- **Cost for R&D, Tech Demos, and Qualification: $200M+**
- **Timeframe: 20-25 Years**

Fuel Efficient S&T Base Participants

6.1 Basic Research

- Advanced Materials & Structures
- Thermal & Fluid Sciences
- Combustion Processes
- Electrochemistry

6.2 Exploratory Development

- Efficient Lightweight Propulsion Components
- High Specific Strength/Stiffness Composite Structures
- Advanced Rotor/Wheel/Track Concepts
- High Energy/Power Density Storage Devices

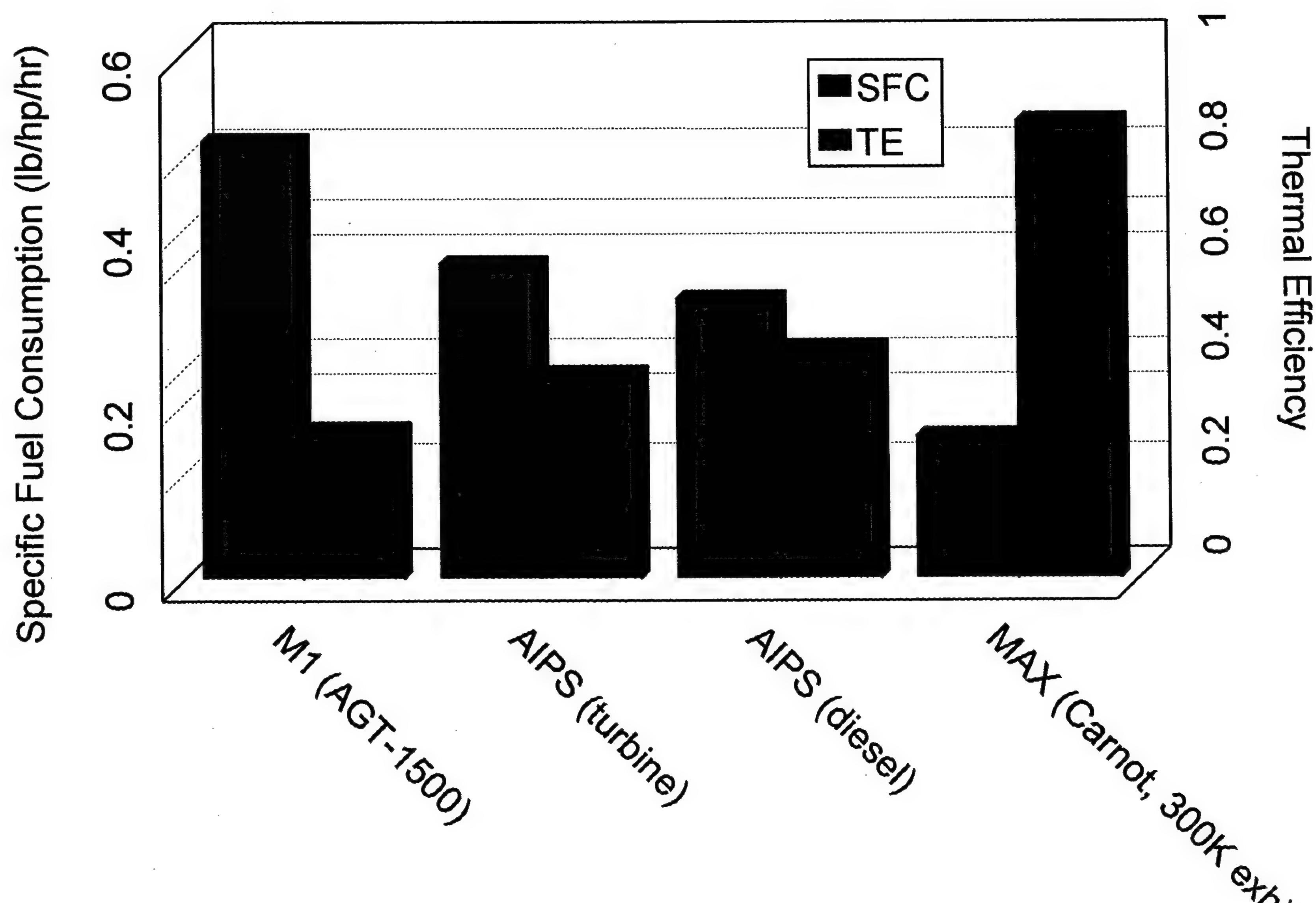
6.3 Advanced Development

- Fuel Efficient Engines
- Power Transfer/Energy Storage Subsystems
- Lightweight Platforms
- Efficient Propulsors

FUEL EFFICIENT AAN
Study Conclusions

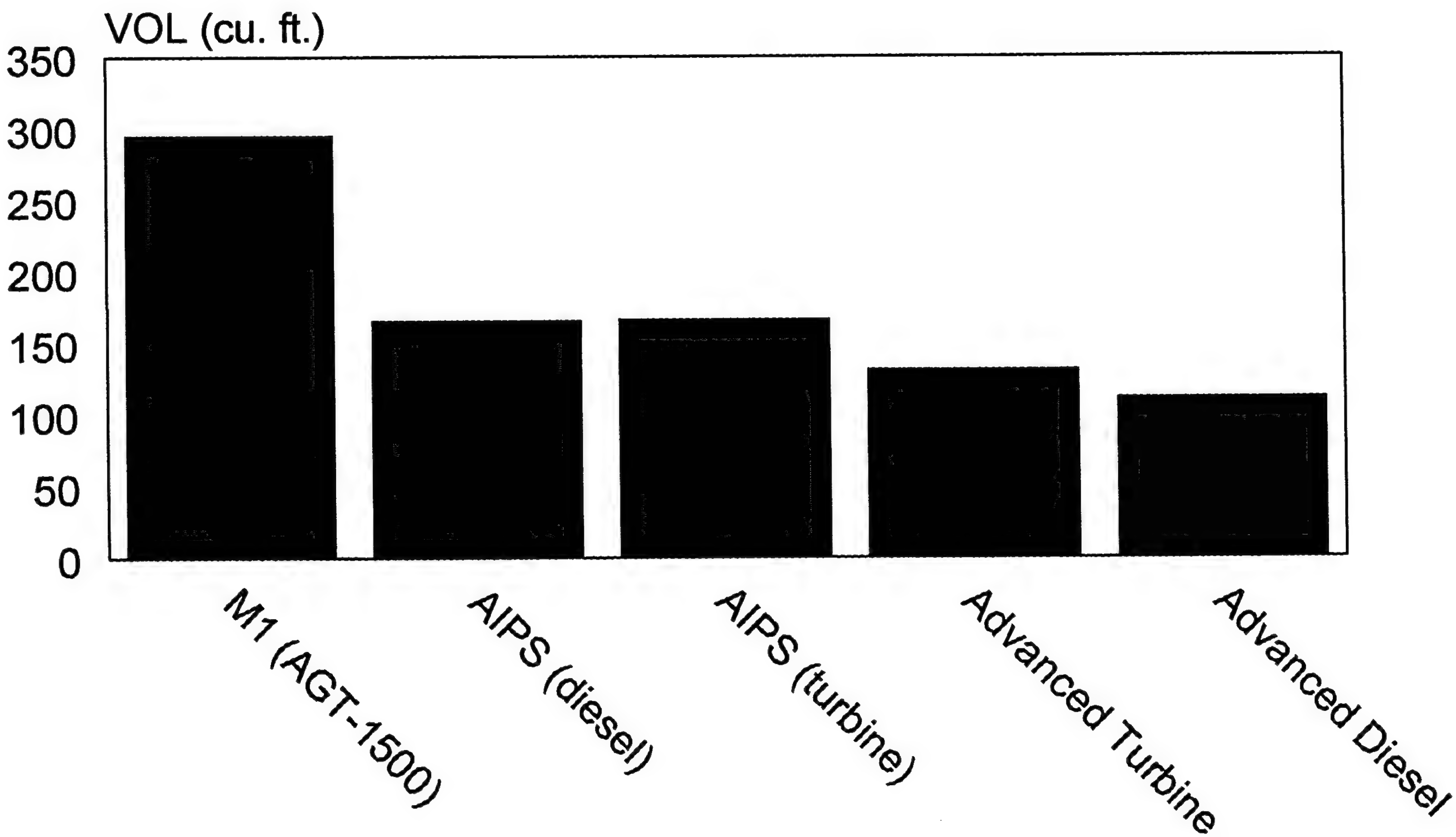
- Substantial BFD savings on the order of 75% are technically feasible in AAN timeframe
- The path to fuel efficiency is based on synergistic interactions among technology areas including:
  - Propulsion
  - Materials and structures
  - Armor
  - Platform configurations
  - Tactics
- Major benefits will result from focus on combat platforms and aviation assets
- Further leveraged benefits will result from reductions in required support infrastructure

Engine Efficiency



Propulsion System Volume

1500 Horsepower: Engine + Fuel + Accessories



Volume Reduction - High Power Density Propulsion

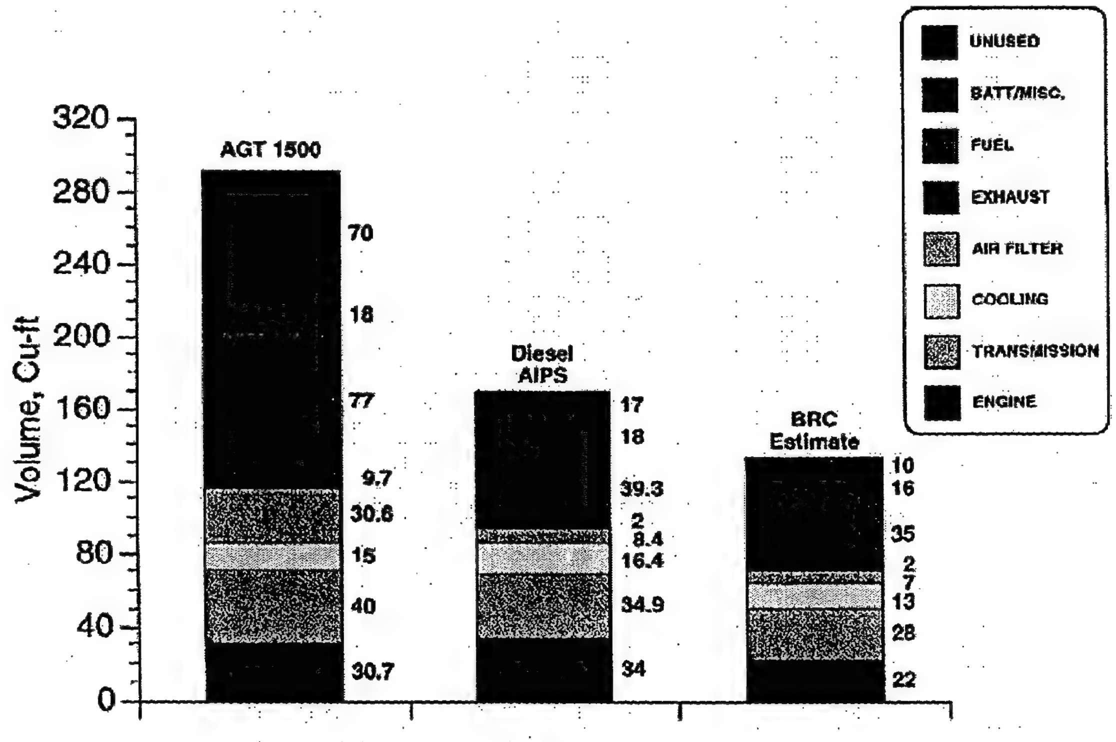


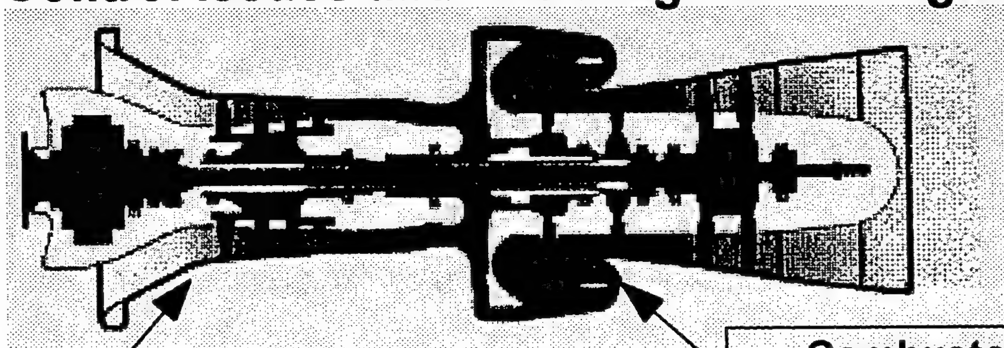
Figure 1-1. Volume reductions achievable by using high power density propulsion systems

TACOM Blue Ribbon Study, November 1995

ENABLING RESEARCH

- Combustion Optimization for High Pressure/High RPM
  -- Design Methodology
  -- Thermal Management
  -- Fuel Injection
- Advanced Controls
  -- Sensors
  -- Actuators
  -- Architecture
- High Temperature Lubrication
- Advanced Materials

Control Issues and Enabling Technologies



Compressor Control
- Surge
- Stall

Combustor Control
- Combustion efficiency
- Emission (soot, NOx,...)
- Stability
- Temperature (liner, exit)
- Ignition (relight, cold)

Enabling Technologies Being Developed
- Nonlinear robust control
- Fuzzy control
- Neural network chips
- MEMS - high temperature applications
- High speed observers for system identification
- Synthetics jets for flow/combustion control
- Smart fuel injectors
- CFD/LES modeling of compressor/ combustor

Presentation on

Georgia Tech's MITE Program

(MITE-Multidisciplinary University Research Initiative on Intelligent Turbine Engines)

Ben T. Zinn
Schools of Aerospace and Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150

Workshop on

Goals and Technologies for Tomorrow's Gas Turbines

Atlanta, Georgia
June 15-16, 1998

Workshop on

Goals and Technologies for Tomorrow's Gas Turbines

<u>**Workshop's Objectives**</u>

- **Discuss/identify problems that adversely affect the performance and cost of operation of gas turbines**
- **Discuss/identify present and future technologies,** especially control technologies, **that could significantly improve gas turbines performance and reduce their ownership cost**
- **Provide a forum for a productive exchange of information between government, industry and university representatives.**

<u>**Workshop's Sessions/Activities**</u>

- **Session I:** **Future Gas Turbines Needs**
- **Session II:** **Control of Compressor Performance**
- **Session III:** **Combustor Design and Control**
- **Session IV:** **Enabling Technologies**
- **Session V:** **Panel Discussion**

Laboratories Tour: Compressor and Combustor Laboratories

MITE Program Objectives

- Develop general
    - Control approaches
    - Sensors/actuators
    - Computational approaches

that will permit engine manufacturers to improve the design process, performance, operability and safety of future gas turbines.

- Demonstrate developed technologies on small-scale experiments
- Transfer developed technologies to industry and government

MITE Research Team

Name	**School**	**Research Area**
Dr. Mark Allen	ECE	MEMS
Dr. Martin Brooke	ECE	Hardware Neural Networks
Dr. Ari Glezer	ME	Flow control/actuators
Dr. Wassim Haddad	AE	Nonlinear control theory
Dr. Jeff Jagoda	AE	Combustion and spray diagnostics
Dr. Suresh Menon	AE	LES of reacting flows
Dr. Y. Neumeier	AE	Control of combustor and compressor processe
Dr. J.V. R. Prasad	AE	Control of compressor instabilities
Dr. L.N. Sankar	AE	CFD of compressor flow
Dr. Jerry Seitzman	AE	Combustion mixing control and sensors
Dr. Ben Zinn	AE/ME	Control of instabilities and combustion process

Supporting Staff: Research engineers, post doctoral fellows, graduate students, machin and electronic shops personnel, computer group, library and administrative support personnel.

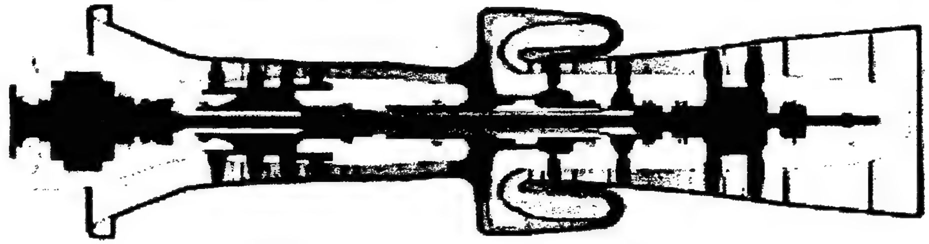
MITE - Experimental Facilities

Facility	Staff
Combustion Laboratory	Jagoda, Glezer, Neumeier Seitzman and Zinn
Computation Facilities	Haddad, Menon and Sankar
Compressor Laboratory	Neumeier and Prasad
Fluid Mechanics Laboratory	Glezer
Microelectronic Research Center Center	Allen and Brooke

Program Studies

- Control of combustor mixing processes (e.g., fuel-air, combustor pattern factor) via synthetic jets
- "Smart" fuel injection systems
- LES of two-phase reacting flows
- Neural net control of combustion processes
- Control of axial and centrifugal compressor stall by passive and active (e.g., flow throttling, fuel flow rate control) means
- Nonlinear control framework for engine compression systems
- CFD of compression systems
- Wireless MEMS pressure sensor for high temperature applications

Control Issues and Enabling Technologies



Compressor Control
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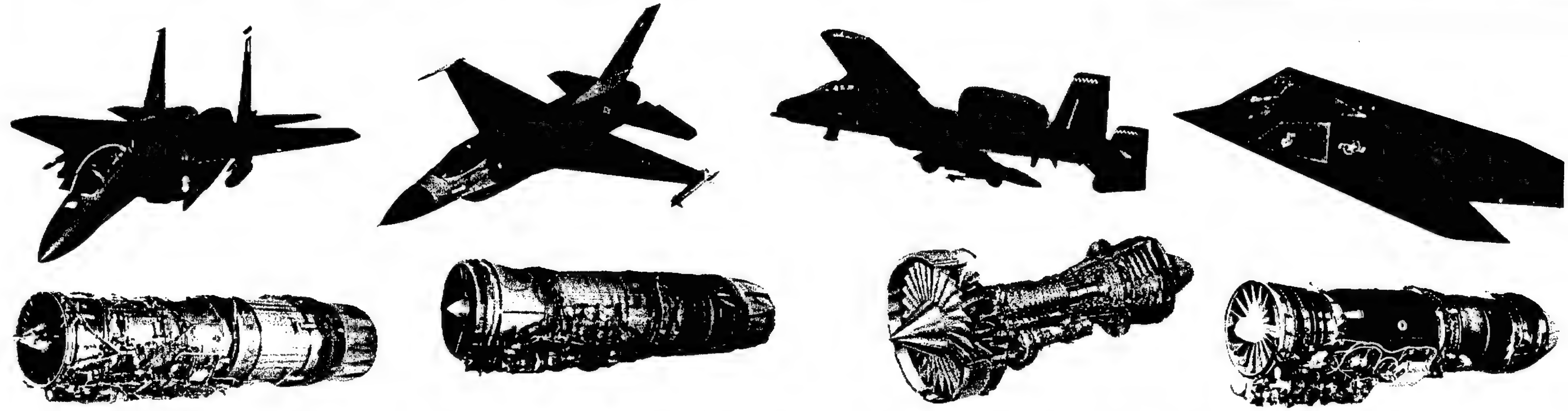
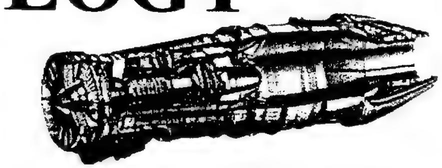
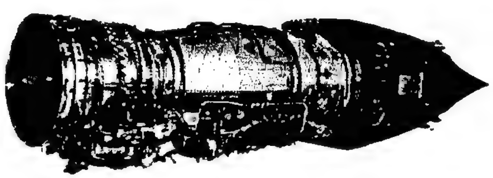


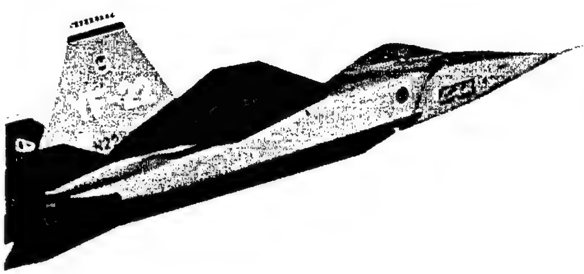
INTEGRATED HIGH PERFORMANCE TURBINE ENGINE TECHNOLOGY

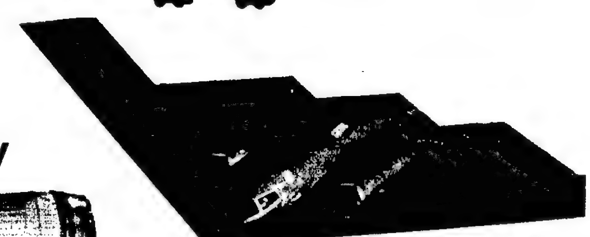


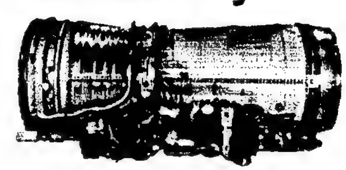
-- IHPTET --



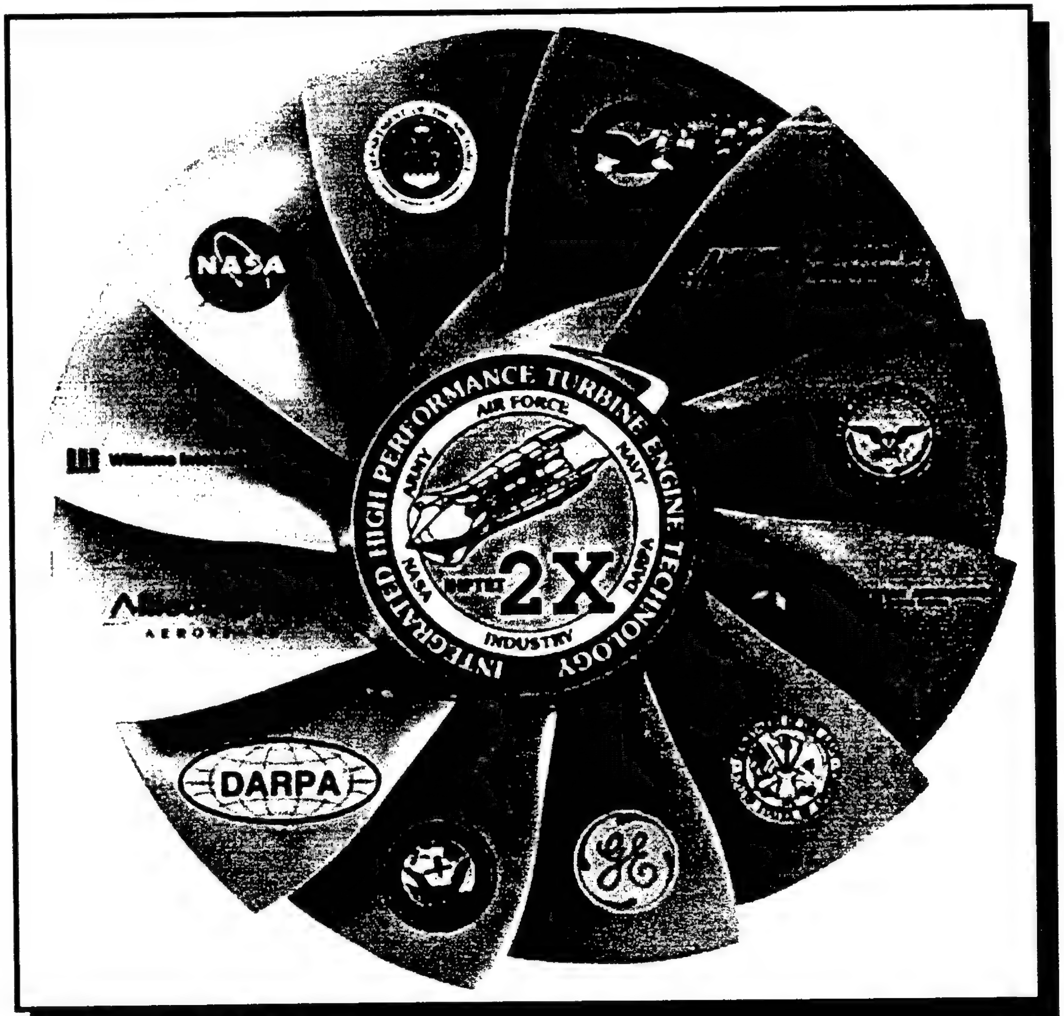
Richard E. Quigley
Deputy Director
Propulsion Directorate
Air Force Research Laboratory







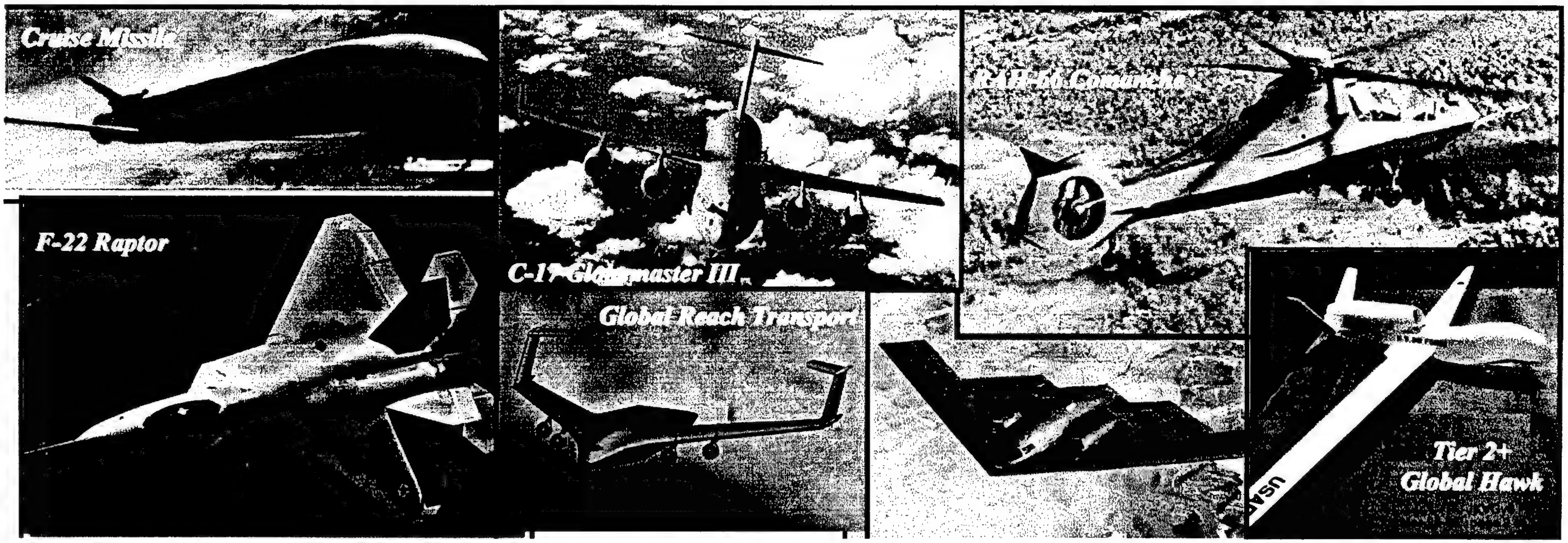
IHPTET:
Government & Industry Working Together



What is <u>IHPTET</u>?

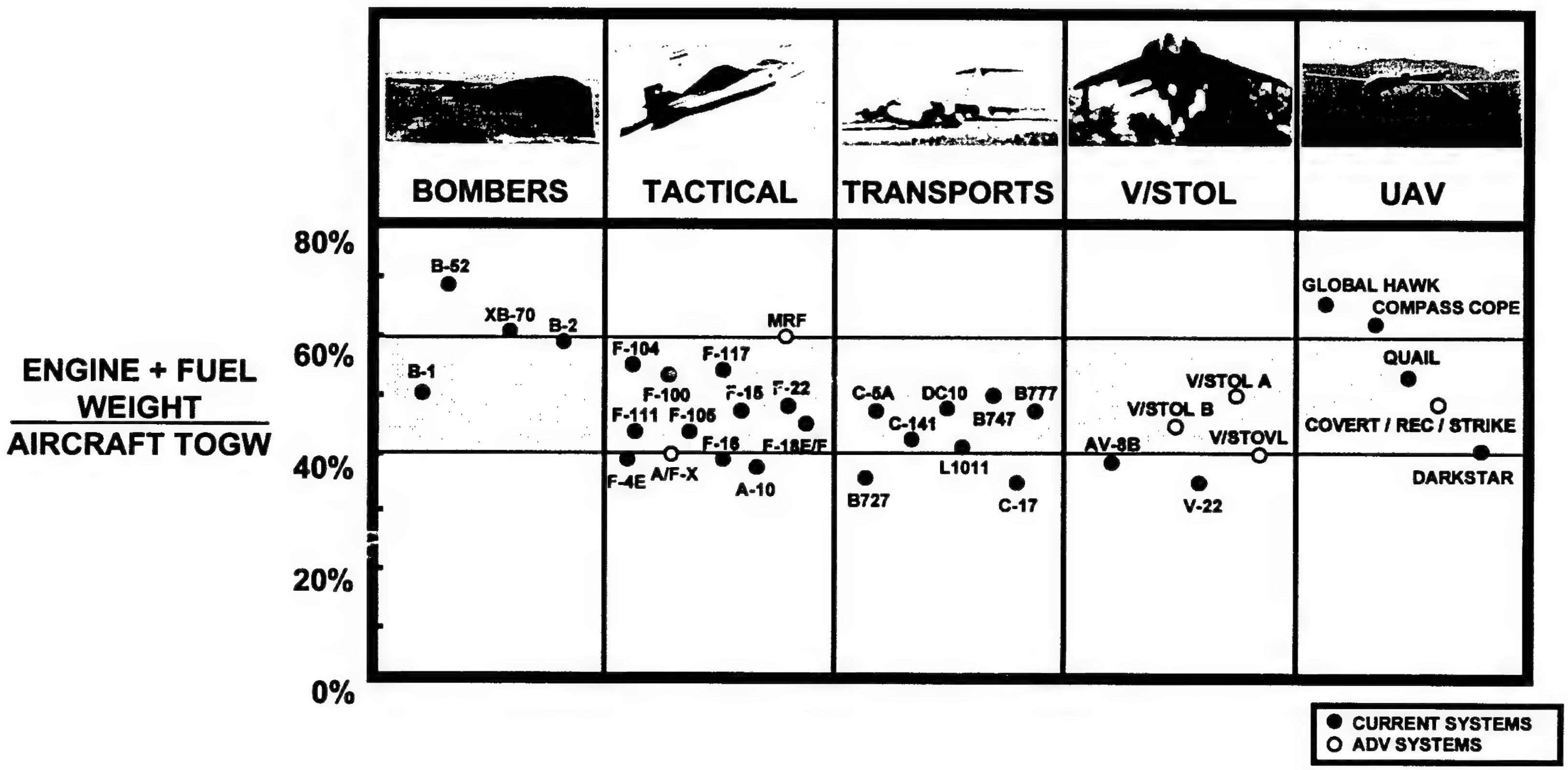
<u>I</u>ntegrated <u>H</u>igh <u>P</u>erformance <u>T</u>urbine <u>E</u>ngine <u>T</u>echnology

The IHPTET program is a joint government and industry effort focused on developing technologies for more affordable, more robust, higher performance turbine engines for current and future aircraft and missile systems.



THE PROPULSION FACTOR

ENGINE PERFORMANCE HAS A MAJOR IMPACT ON AIRCRAFT SIZE



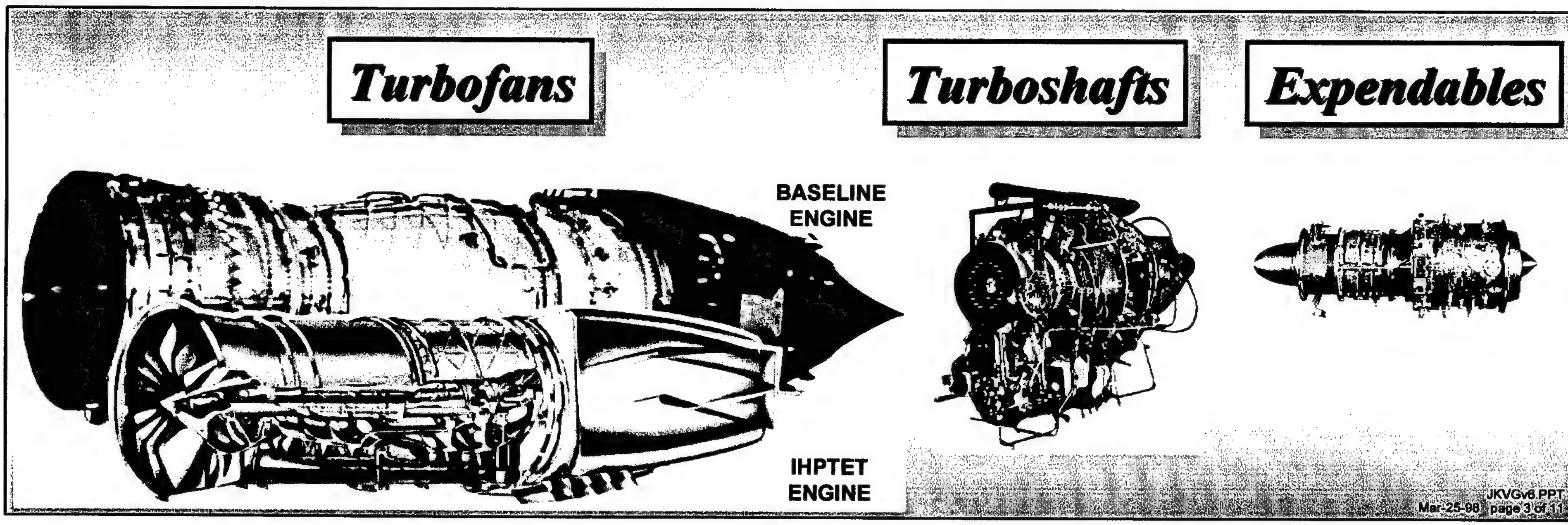
- 40 - 60% OF AIRCRAFT TAKEOFF GROSS WEIGHT
- 20 - 40% OF TOTAL WEAPON SYSTEM LIFE CYCLE COST

IHPTET Goals

DOUBLE AIRCRAFT AND MISSILE PROPULSION PERFORMANCE

while

DECREASING MANUFACTURING AND MAINTENANCE COSTS 35% BY 2003

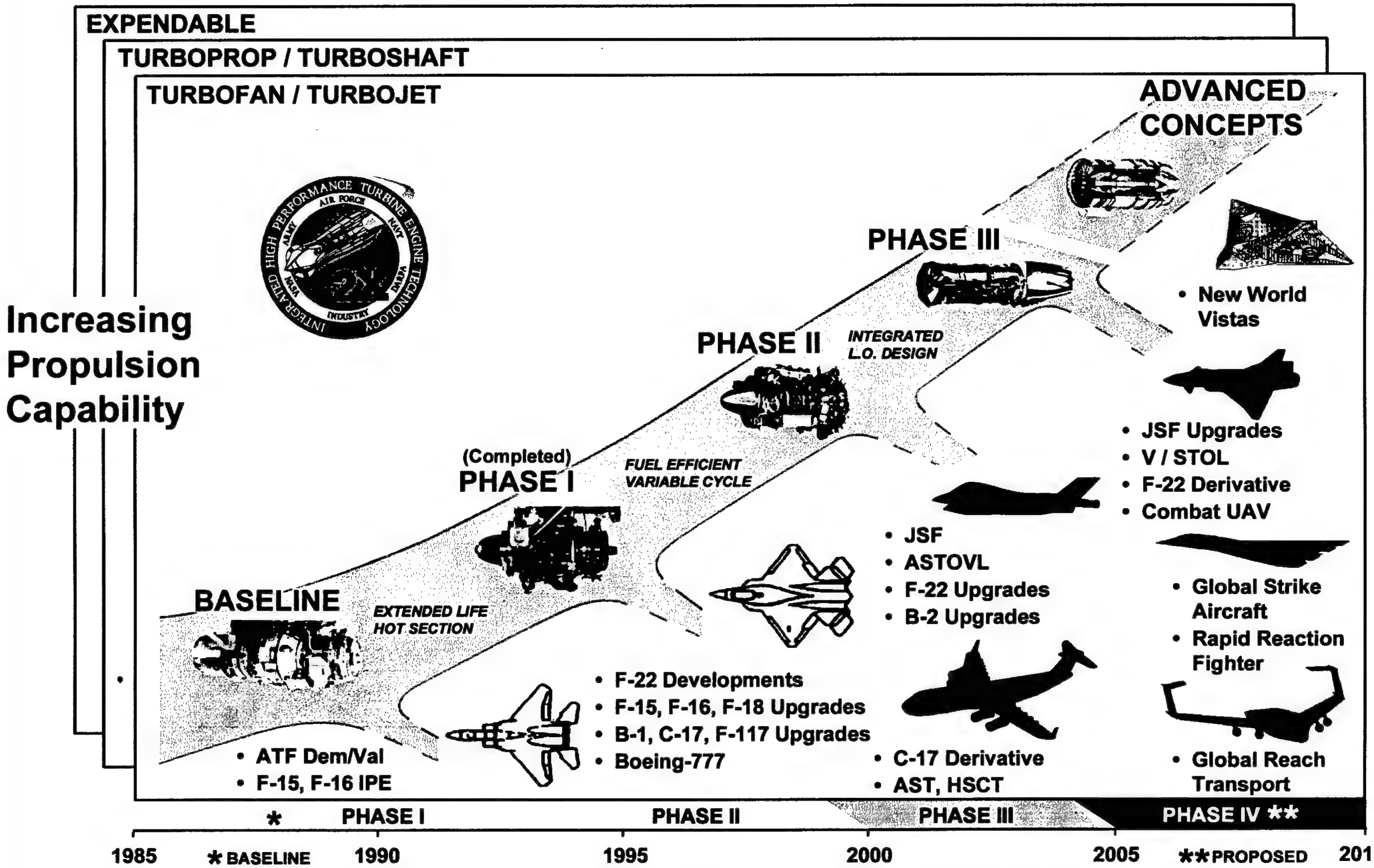


IHPTET Goals are Time Phased *

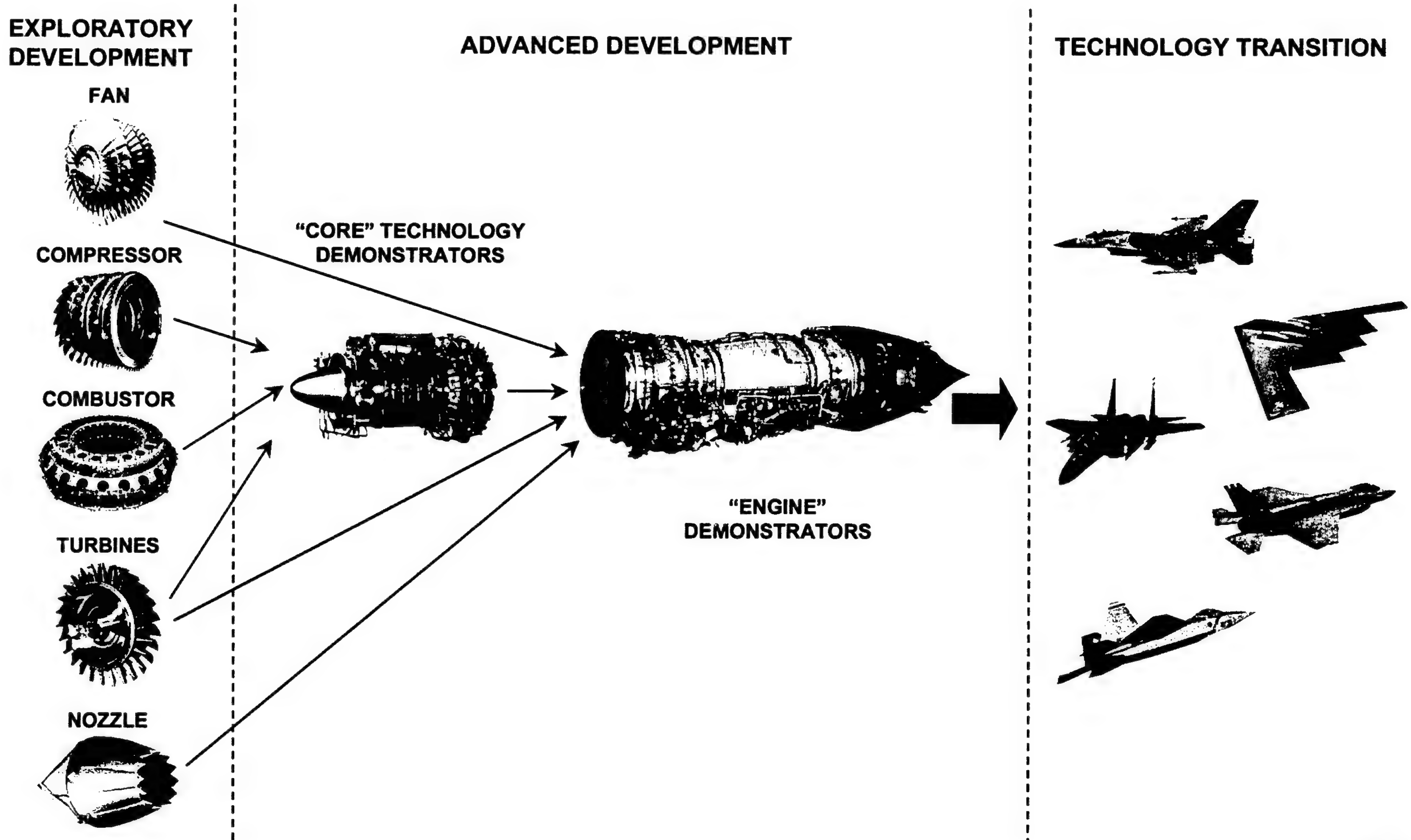
	PHASE I 1991	PHASE II 1997	PHASE III 2003	STATUS
[illegible]				
THRUST / WEIGHT RATIO	+30%	+60%	+100%	+37%
COMBUSTOR INLET TEMP	+100°F	+200°F	+400°F	+60°F
PRODUCTION COST	---	-20%	-35%	-12%
MAINTENANCE COST	---	-20%	-35%	-4%
[illegible]				
SPECIFIC FUEL CONSUMPTION	-20%	-30%	-40%	-22%
POWER / WEIGHT RATIO	+40%	+80%	+120%	+63%
PRODUCTION COST	---	-20%	-35%	-18%
MAINTENANCE COST	---	-20%	-35%	-3%
[illegible]				
SPECIFIC FUEL CONSUMPTION (STRATEGIC)	-20%	-30%	-40%	0%
THRUST / AIRFLOW RATIO (TACTICAL SUPERSONIC)	+35%	+70%	+100%	+39%
PRODUCTION COST	-30%	-45%	-60%	-39%

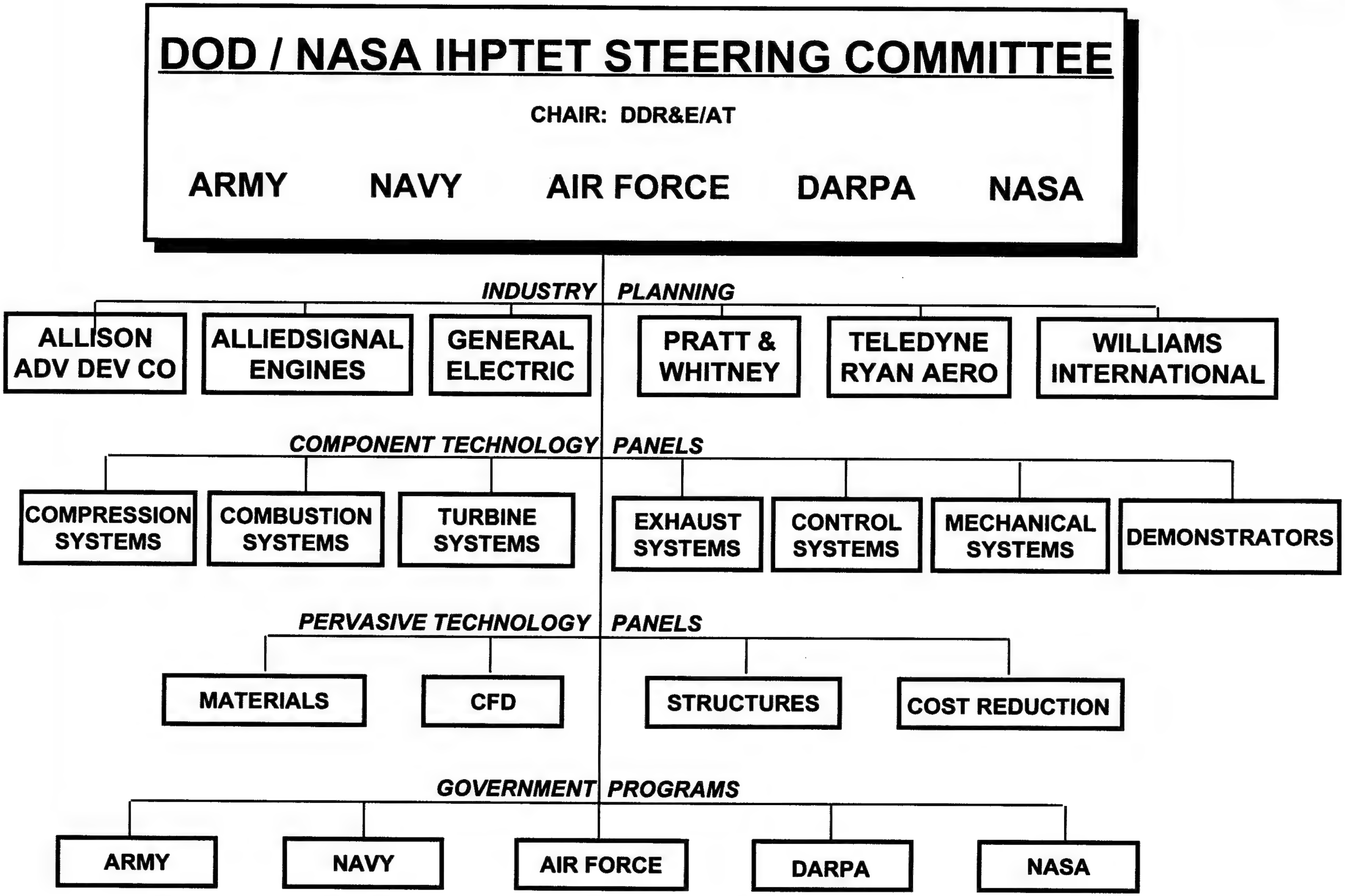
* REFERENCE 1987 STATE OF THE ART, AT CONSTANT LIFE

Phased Approach Enhances Transition



IHPTET
TECHNOLOGY DEVELOPMENT APPROACH



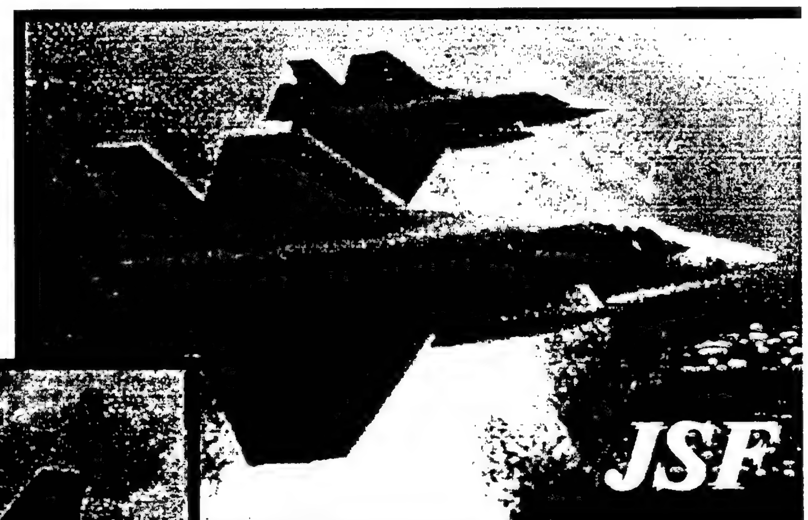

DOD / NASA IHPTET STEERING COMMITTEE
CHAIR: DDR&E/AT
ARMY
NAVY
AIR FORCE
DARPA
NASA
INDUSTRY PLANNING
ALLISON ADV DEV CO
ALLIEDSIGNAL ENGINES
GENERAL ELECTRIC
PRATT & WHITNEY
TELEDYNE RYAN AERO
WILLIAMS INTERNATIONAL
COMPONENT TECHNOLOGY PANELS
COMPRESSION SYSTEMS
COMBUSTION SYSTEMS
TURBINE SYSTEMS
EXHAUST SYSTEMS
CONTROL SYSTEMS
MECHANICAL SYSTEMS
DEMONSTRATORS
PERVASIVE TECHNOLOGY PANELS
MATERIALS
CFD
STRUCTURES
COST REDUCTION
GOVERNMENT PROGRAMS
ARMY
NAVY
AIR FORCE
DARPA
NASA

JKVGv6.PPT

IHPTET has <u>Large Military Importance</u>

The F-22 and Joint Strike Fighter (JSF) programs *need* IHPTET technologies to meet future requirements

Sustained Supersonic Cruise

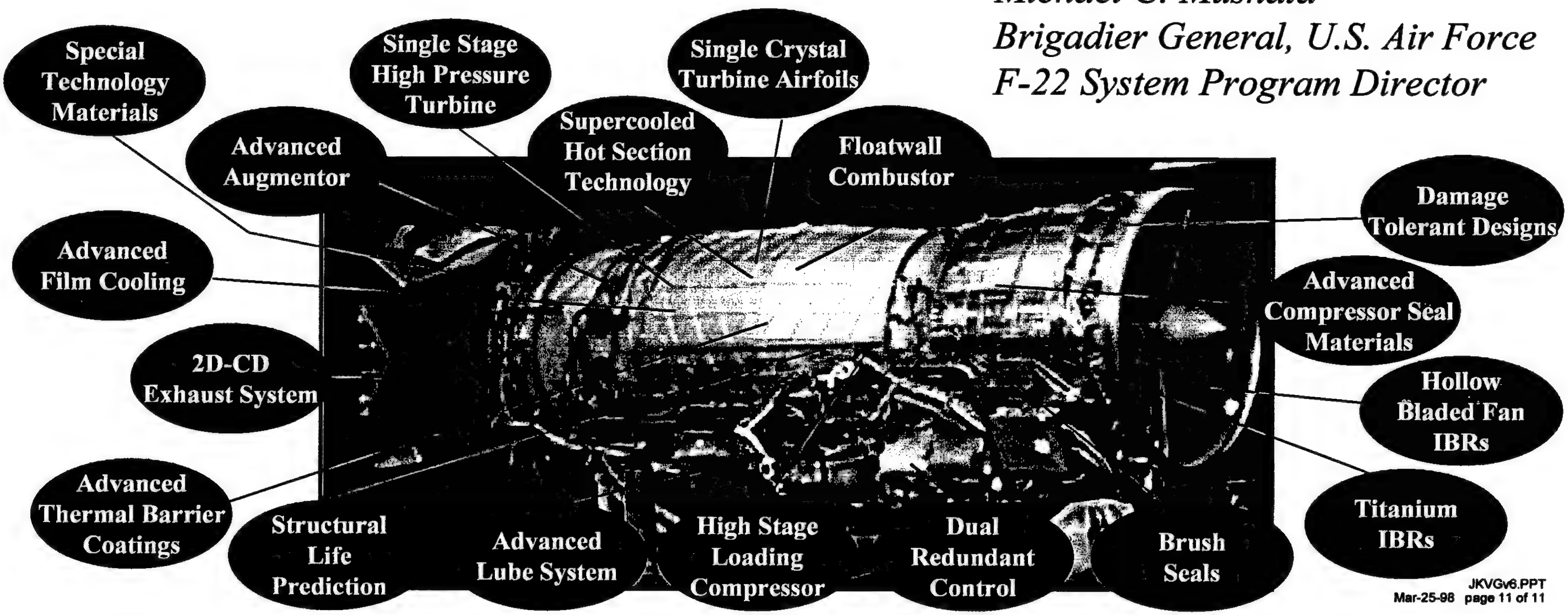


Short Take-off / Vertical Landing

IHPTET Technologies are Transitioning

"Our F119 engine derived a substantial number of advanced technologies from the IHPTET program .... There is a tremendous opportunity to incorporate additional emerging IHPTET technologies ...."

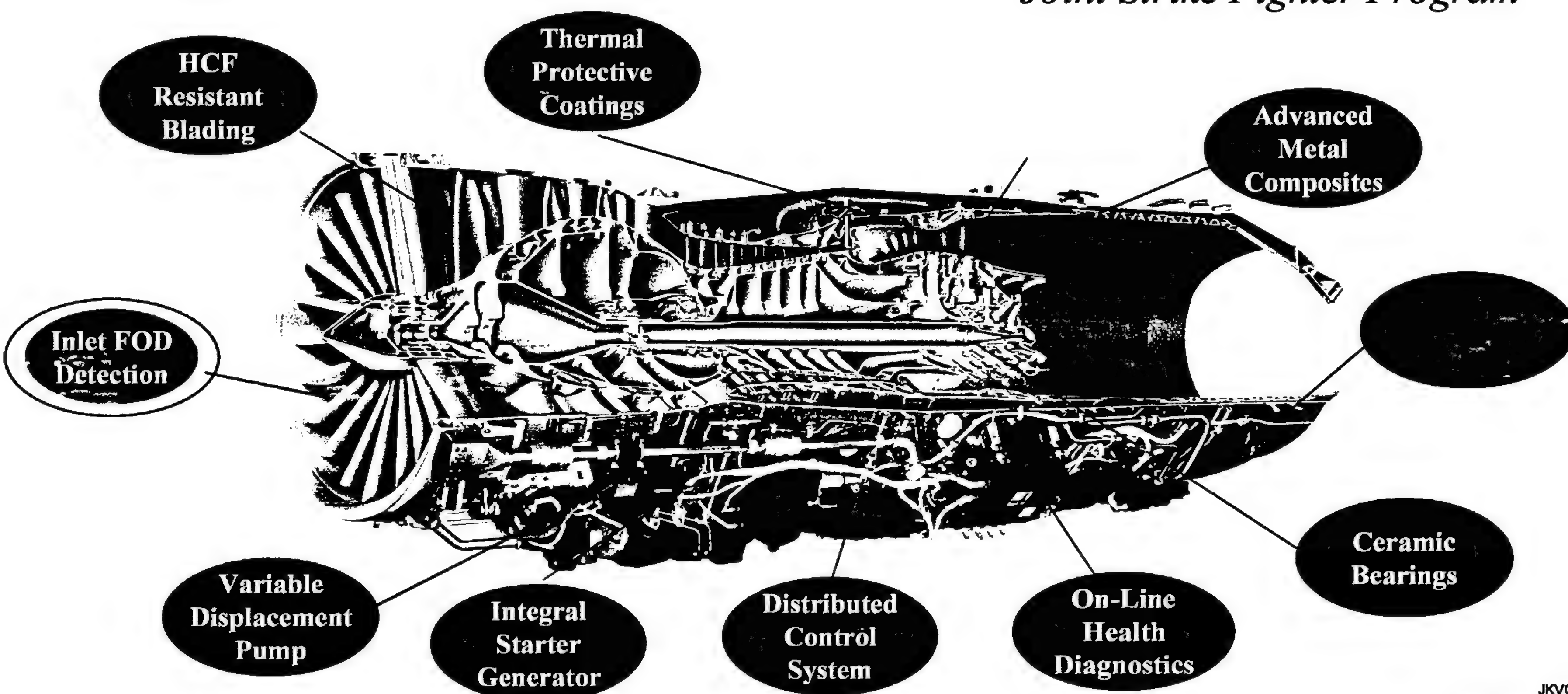
Michael C. Mushala
Brigadier General, U.S. Air Force
F-22 System Program Director



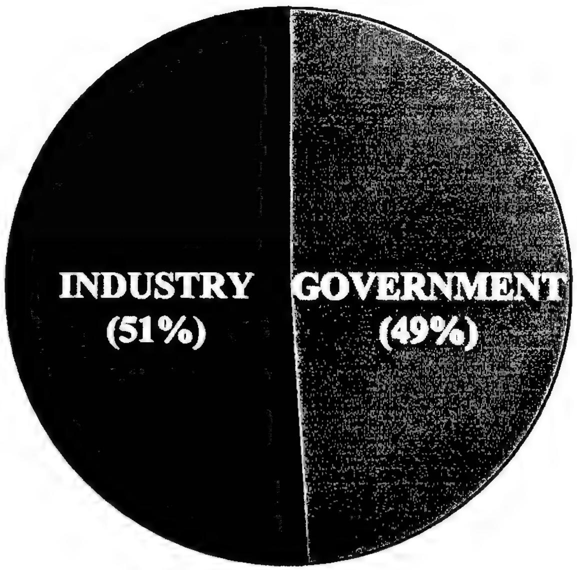
... and Will <u>Continue to Transition</u>

"A robust and healthy IHPTET program is vital to the JSF program."

Leslie F. Kenne
Brigadier General, U.S. Air Force
Joint Strike Fighter Program



IHPTET Funding is <u>Reasonable</u>



<u>Government Investment</u>

<2% of Total DoD S&T Budget

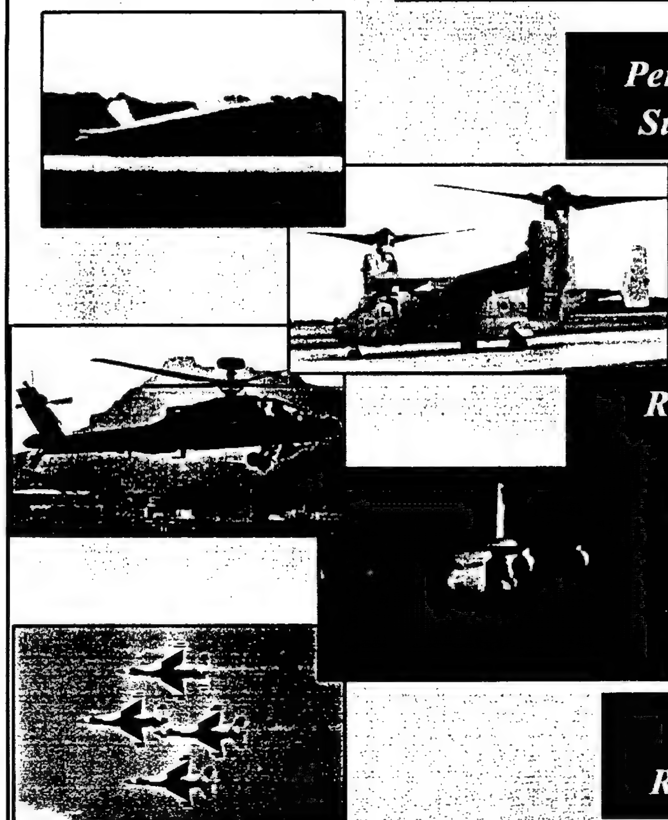
<u>Government + Industry Investment</u>

<2% of Domestic Engine Sales

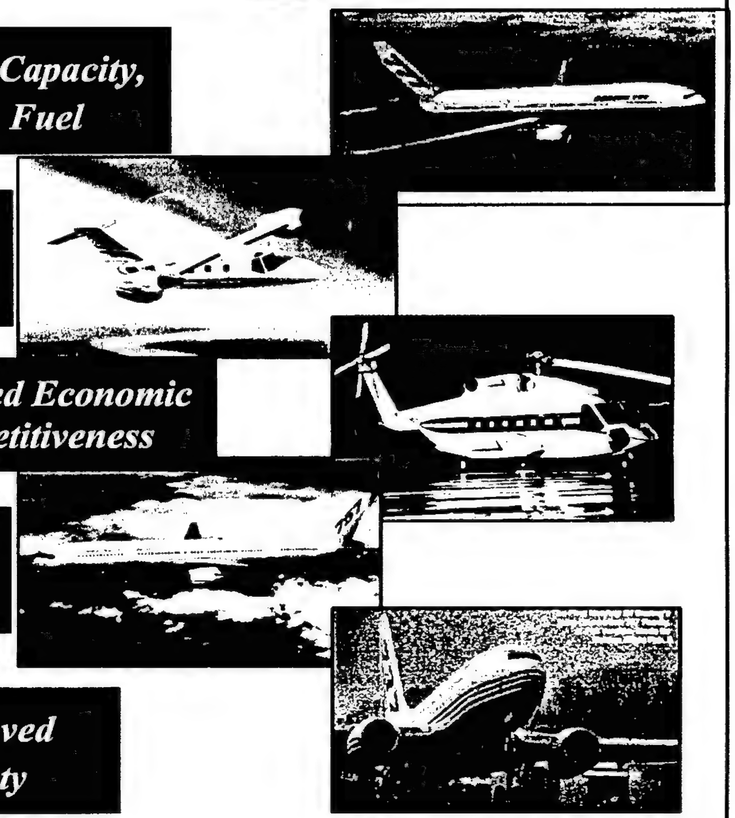
FY88-FY97 FUNDING - *$2.5B*

IHPTET Contributes to Global Competitiveness

Military Enablers → **transition** → *Commercial Benefits*

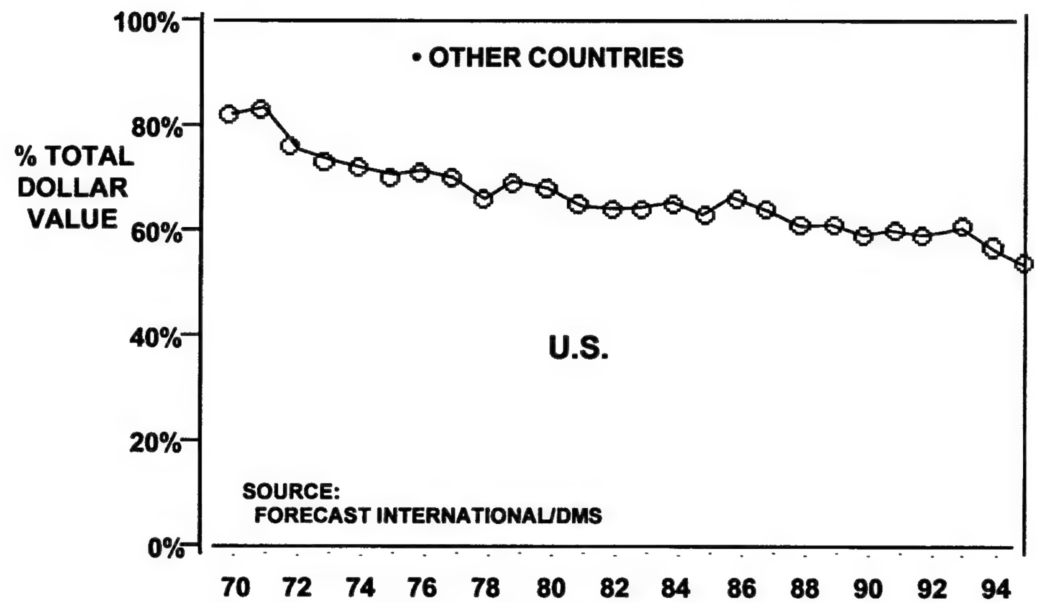


Military Enablers	Commercial Benefits
Performance Superiority	*Greater Capacity, Less Fuel*
More Power	*Unique Propulsion Solutions*
Reduced Cost	*Enhanced Economic Competitiveness*
Longer Range	*New Markets*
Better Reliability	*Improved Safety*

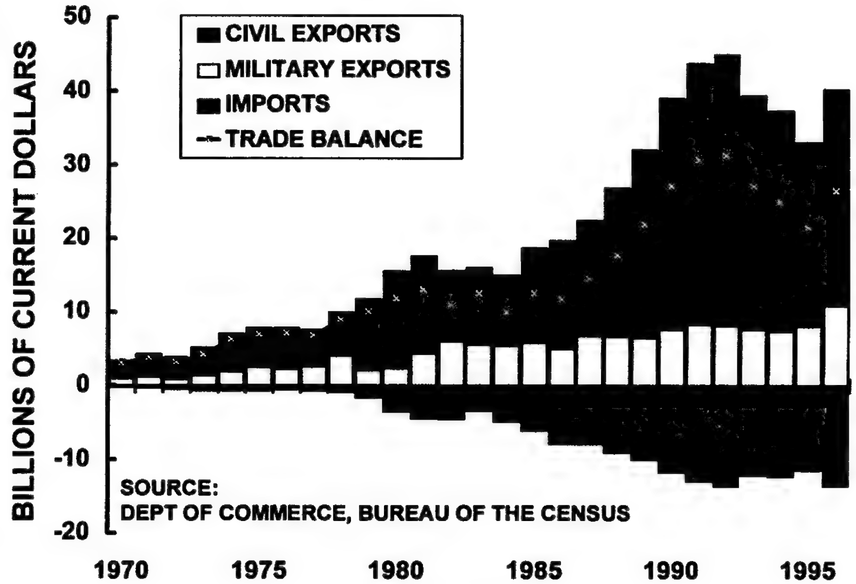


IHPTET Contributes to Economic Competitiveness

ENGINE INDUSTRY WORLD MARKET SHARE

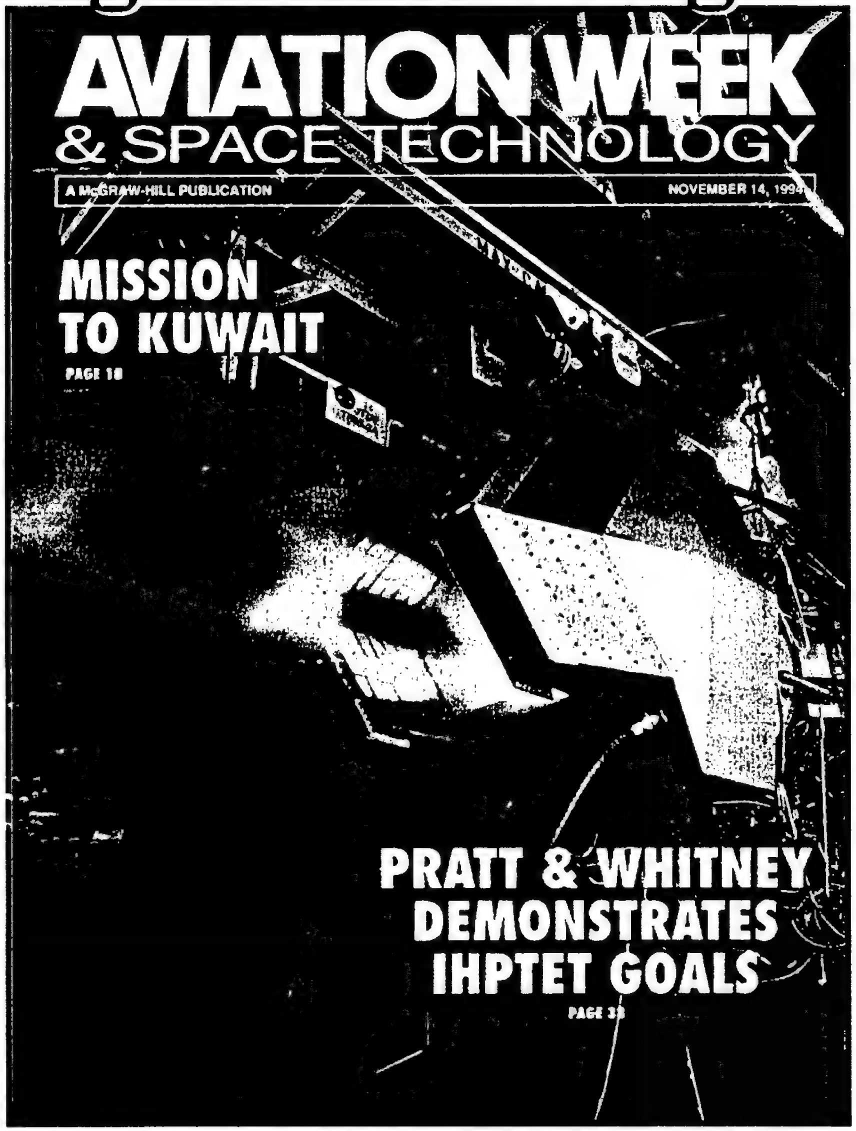


AIRCRAFT INDUSTRY TRADE BALANCE



- U.S. DEFENSE DEPENDENT UPON VIABLE ENGINE INDUSTRY

IHPTET Has Achieved Significant Progress Toward the Goals

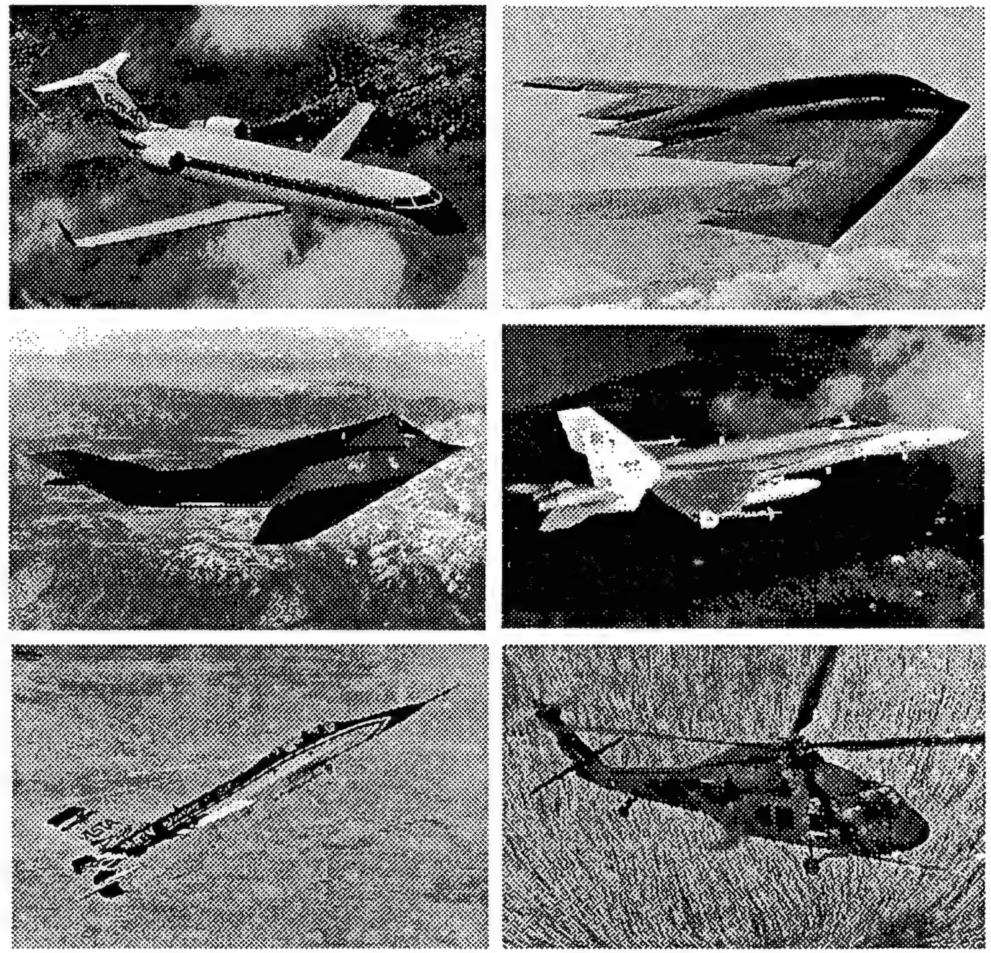


IHPTET is a Model S&T Program

- *IHPTET Has Large Military Importance*
- *IHPTET Technologies are Transitioning*
- *IHPTET Funding is Reasonable*
- *IHPTET Contributes to Global Competitiveness*
- *IHPTET Has Achieved Significant Progress Toward the Goals*

Propulsion Technologies for the 21st Century

June 15, 1998



H.M. Maclin
Manager, Advanced Miltary
Engine Technology

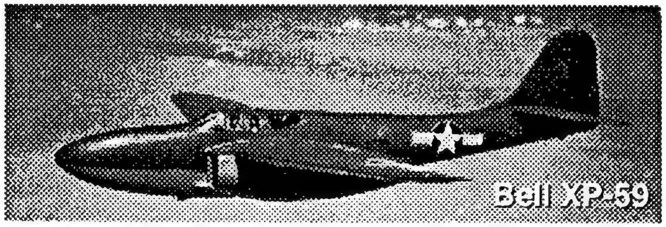
GE Aircraft Engines

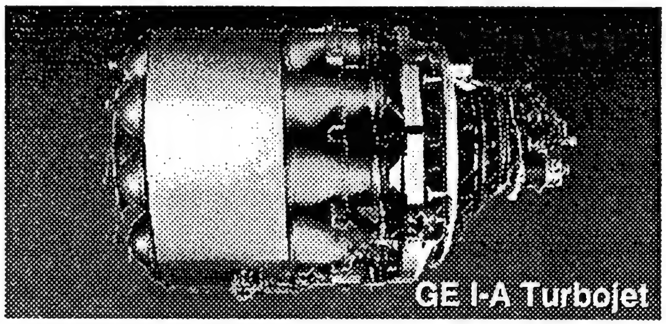
PPTMAC9-83365-091195

Evolution of Jet Engine Technology

50 Years of Progress

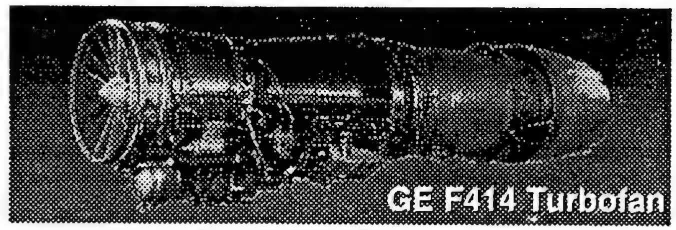
1942


Bell XP-59


GE I-A Turbojet

Today


F/A-18E/F Advanced Hornet

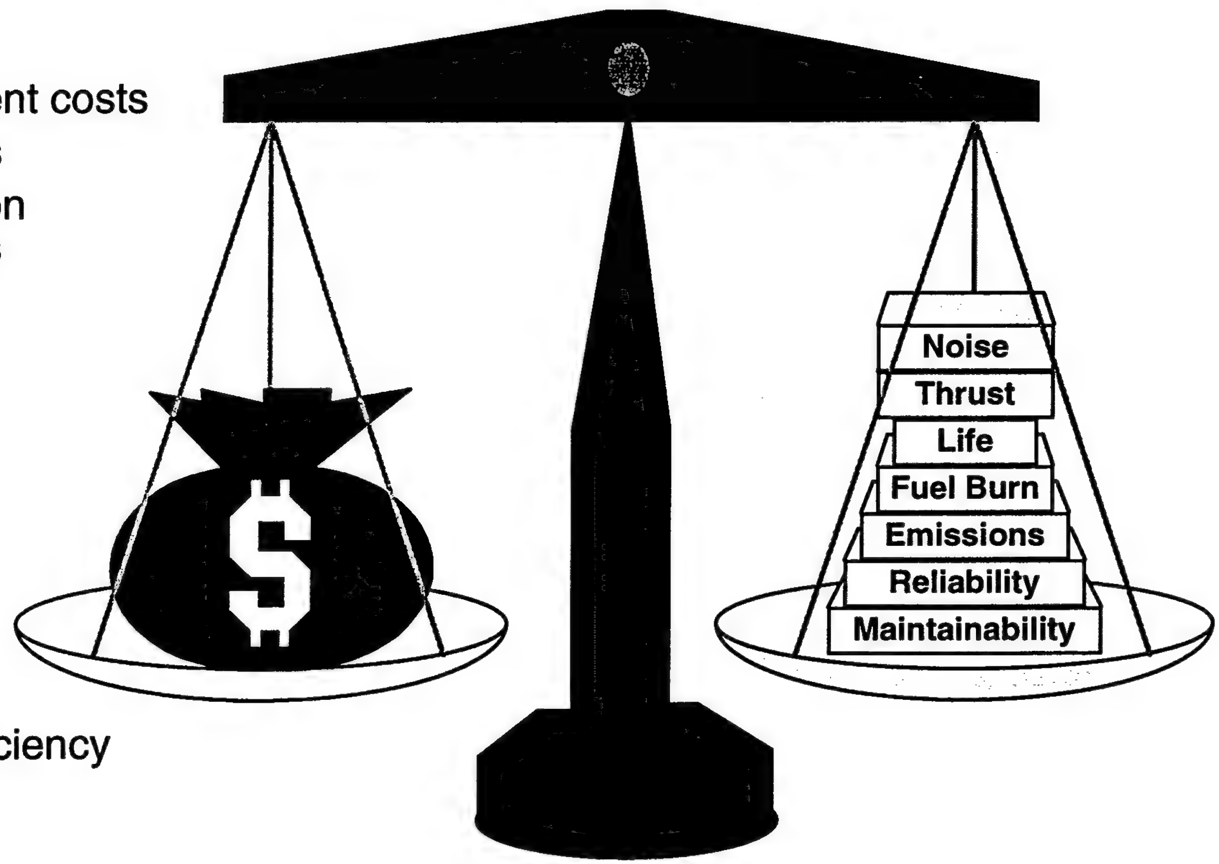

GE F414 Turbofan

Level of Technology	1942	Today	2020
Thrust/Weight	1.6 : 1	9 : 1	15 : 1
Turbine Inlet Temperature	1500°F	2800°F class	3000+°F
Engine Life	7.5 hours	2000 hours	4000 hours
Fuel Efficiency	Base	46% Better	65% Better

What Will the Next 50 Years Bring?

Key Market Drivers for Aircraft Propulsion

- Cost
  - Lower development costs
  - Lower initial costs
  - Reduced operation and support costs
  - Higher reliability
  - Longer life
- Environment
  - Noise
  - Emissions
  - "Stealthiness"
- Performance
  - Higher thrust
  - Improved fuel efficiency
  - Lower weight



Affordability and performance must be balanced

Customer Demands for Future Propulsion Systems

Commercial Transports

- More affordable
  - Buy
  - Own
- More useful payload
- Longer range
- Longer time on wing
- Improved dispatch reliability
- Reduced emissions
- Reduced IFSD rate

Military Aircraft

- More affordable
  - Develop
  - Buy
  - Own
- More useful payload
- Increased range and loiter
- Reduced size
- Increased maneuverability
- Reduced vulnerability
- Increased robustness

Customer Needs Related to Options for Design Execution

+ Favorable Impact
– Unfavorable Impact

Customer Needs

Options for Design Execution	SFC ⇩	Weight ⇩	Acg $ ⇩	Overhaul $ ⇩	Maint $ ⇩	Component Life ⇧	Noise ⇩	Emissions ⇩	Dev Hdwre Test ⇩	Thrust/Airflow ⇧
Bypass Ratio ⇧	+	–	–				+			–
Overall Pressure Ratio ⇧	+	–	–	–				–		
Turbine Inlet Temperature		+	–	–	–					+
Imprvd Design Analysis Tools	+	+	+	+	+	+	+	+	+	+
Higher Temp Materials	+	+	–	–	–					–
Component Efficiencies ⇧	+	+	+					+		+
Cooling Flow ⇩	+	+						+		+
Stage Loading ⇧		+	+	+	+					
Material Strength/Density ⇧		+								+
Low Emisssions Combustor Tech			–					+		
Integrated Thermal Mgmt	+	+	+							+

Trade studies are needed to balance requirements with design options for selection of cost effective solutions

Translation of Military Customer Requirements to Design Metrics

Military Aircraft

- More affordable
  - -Develop
  - -Buy
  - -Own
- More useful payload
- Increased range and loiter
- Reduced size
- Increased maneuverability
- Reduced vulnerability

Propulsion Design Metrics

Development hdwre ⇩ & testing ⇩

Acquisition cost ⇩

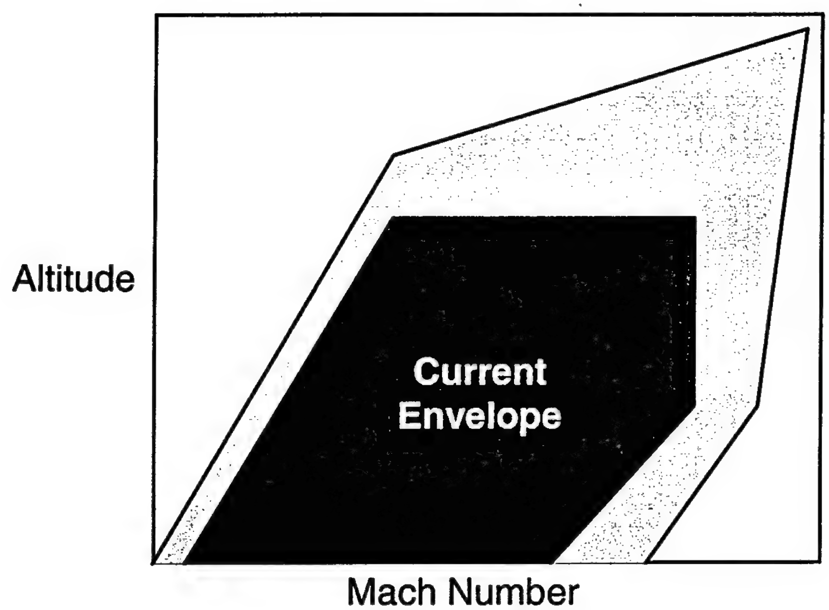
Maintenance cost ⇩
Component life ⇧
Overhaul cost ⇩

SFC ⇩ , Weight ⇩

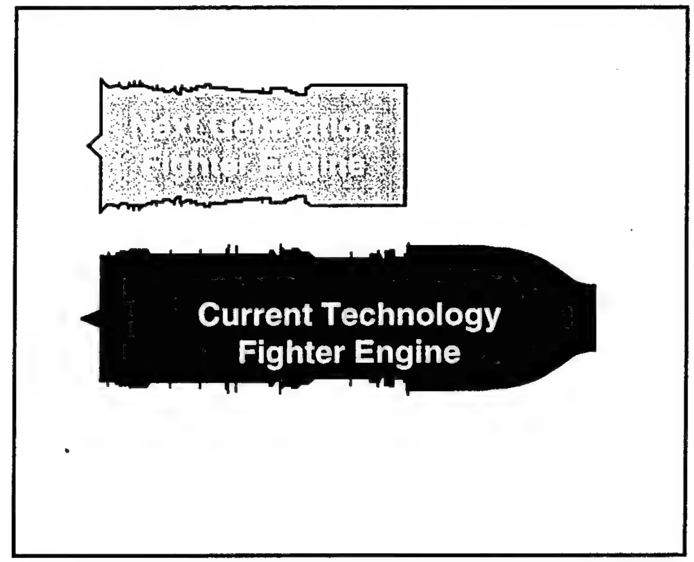
Thrust/airflow ⇧ , weight ⇩

Future Goals

Expanded Flight Envelope



Reduced Size, Weight, Cost, and Complexity



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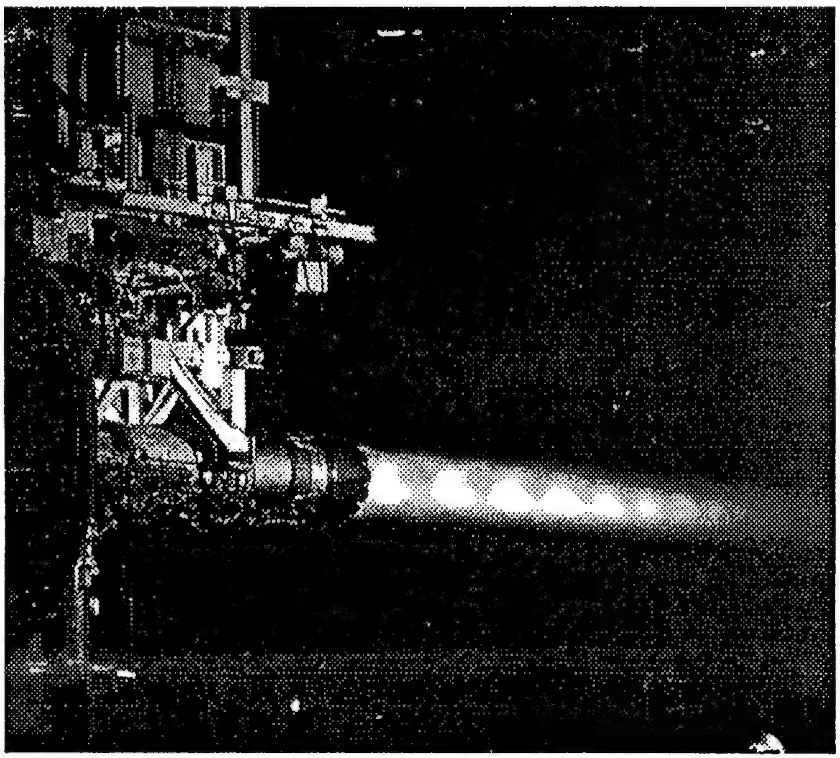
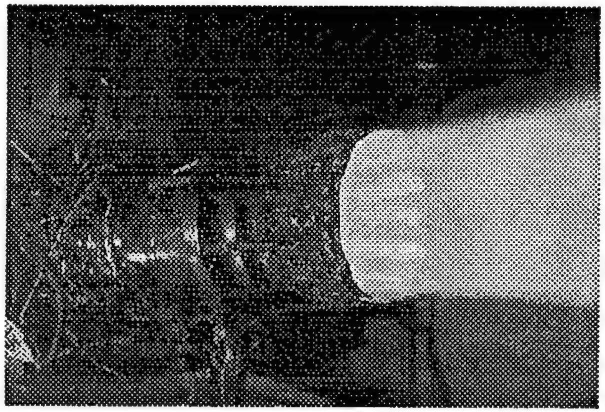
Core Technology Development



- Materials
- Analytical Design Tools
- Components

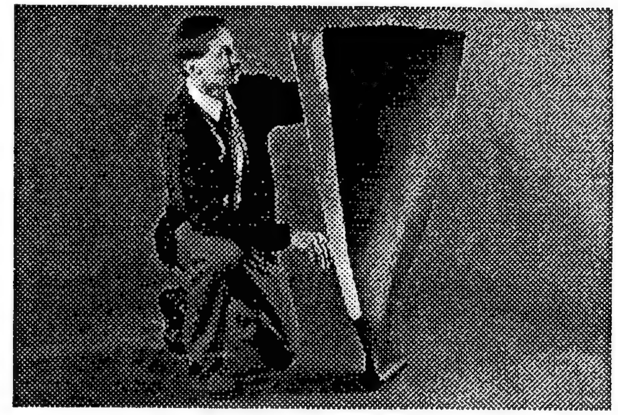
Advanced Materials

Ceramic Matrix Composites (CMC)



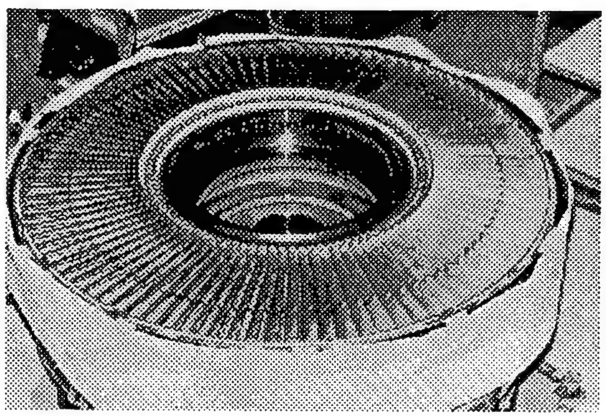
F414 Exhaust Nozzle - 4X Life Increase

Organic Matrix Composites (OMC)



Lightweight GE90 Fan Blades Save 700 Pounds

Intermetallics

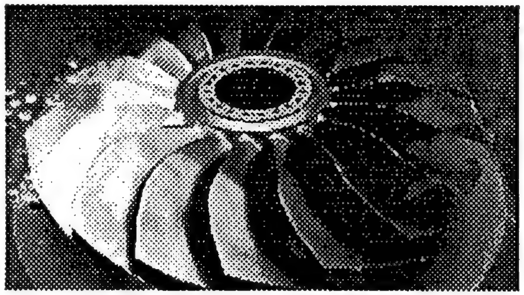


Lightweight, High Temperature Blade Material

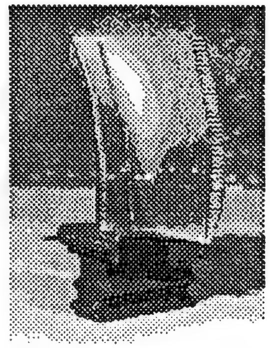
Metal Matrix Composites (MMC)

High Strength-to-Weight Properties

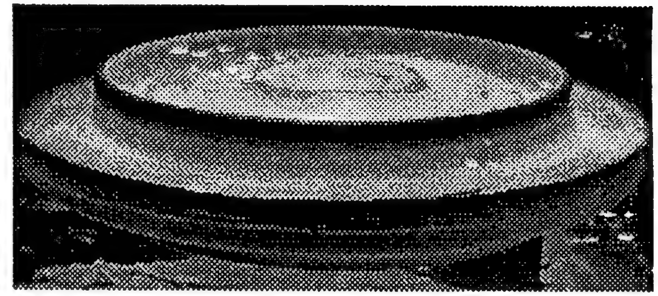
Component Technologies



Hollow Swept Fan & Compressor Blades

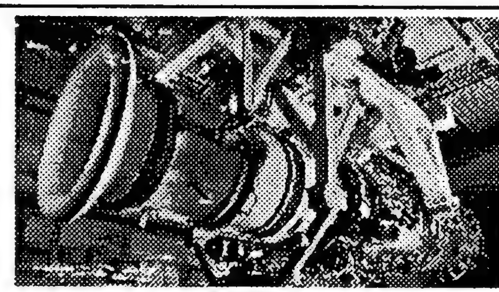


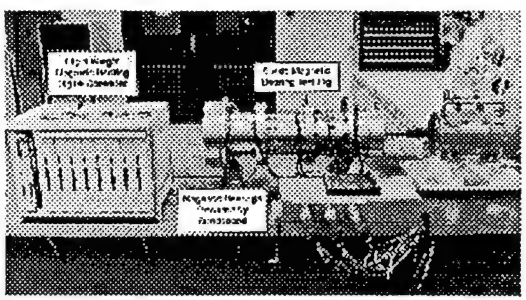
High Temperature Turbines



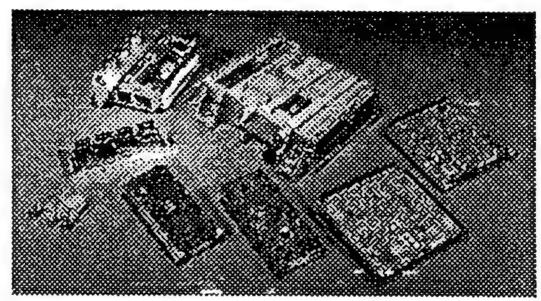
Long Life Dual Alloy Disk

USAF & USN
Joint Technology
Demonstrator Engine



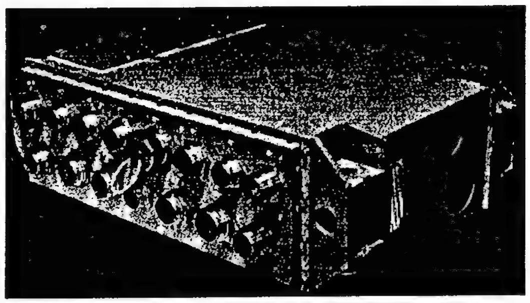


Magnetic Bearings (Test Rig)

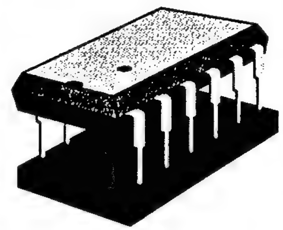


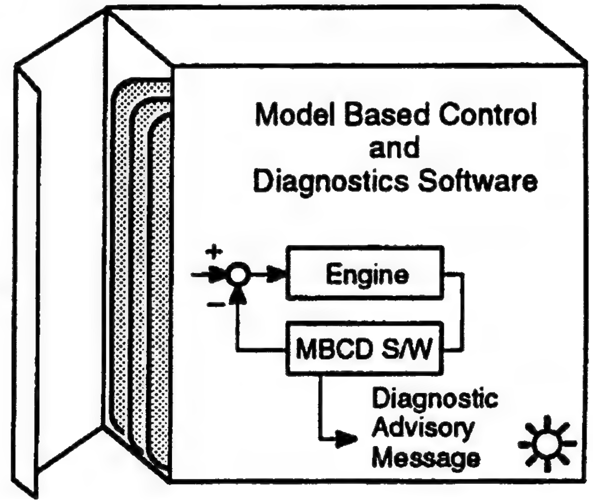
Advanced Digital Controls

Controls and Diagnostics



FADEC

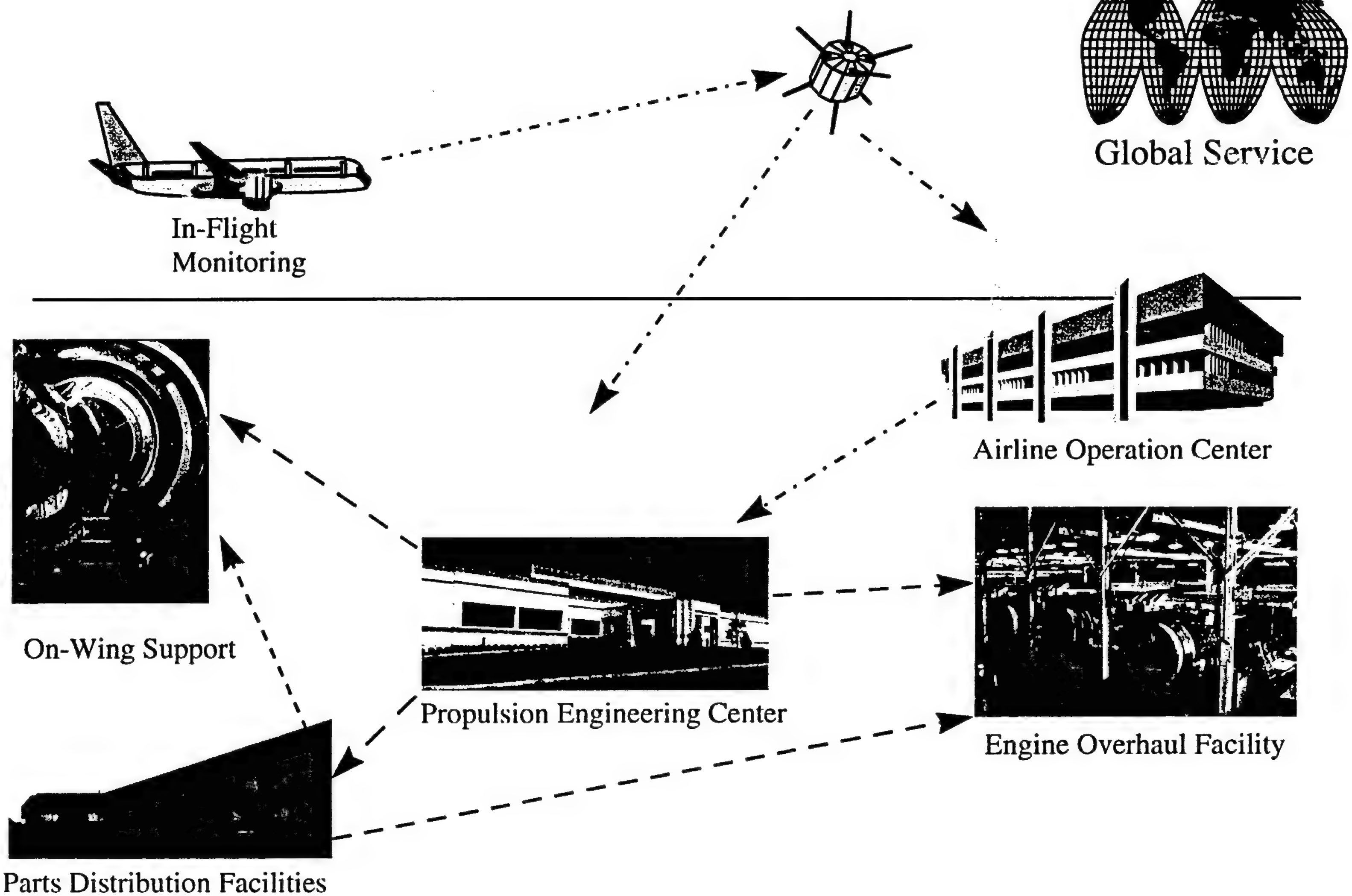




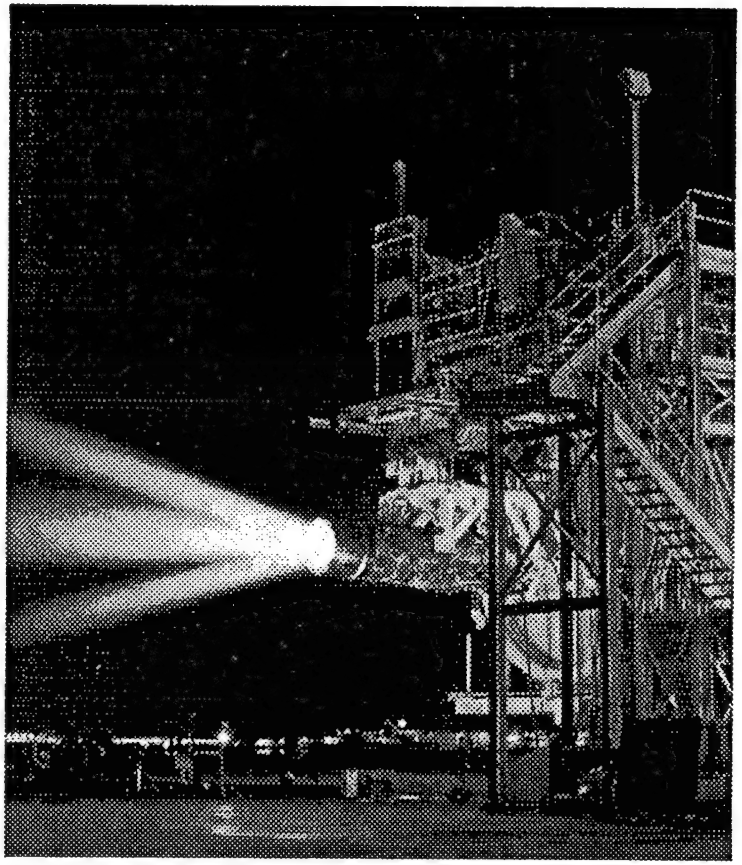
- *Model Based Diagnostics*
- *Redundant Sensors*
- *Enhanced Logic*
- *Variable Displacement Fuel Pump*

- Reduced fuel system part count/complexity
- Improved fault isolation/failure tolerance
- Reduced IFSD, power losses
- Optimized performance, operability, vehicle management, system integration

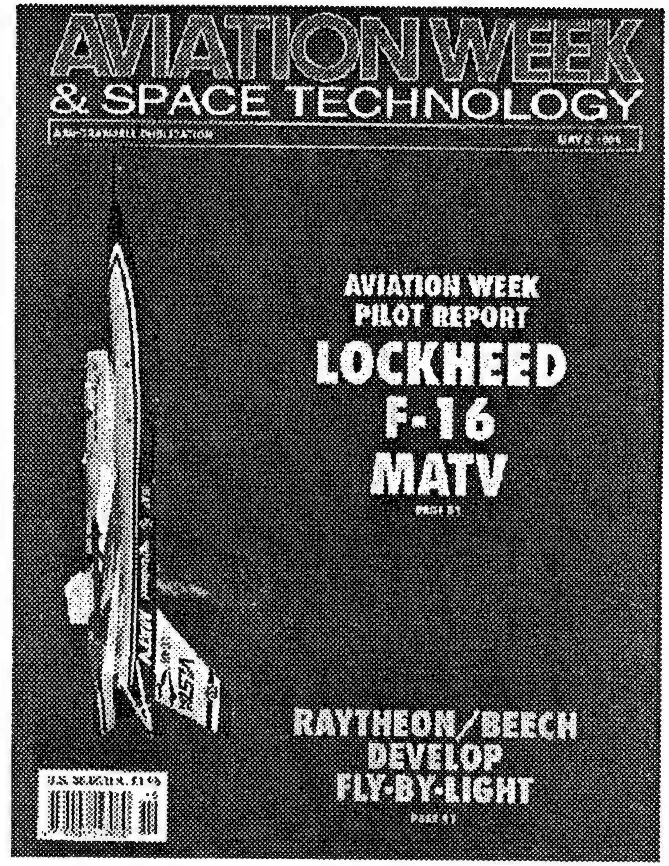
GEAE Remote Services Delivery Process



Thrust Vectoring



AVEN® – Axisymmetric Vectoring Exhaust Nozzle



Used with permission of
Aviation Week & Space Technology

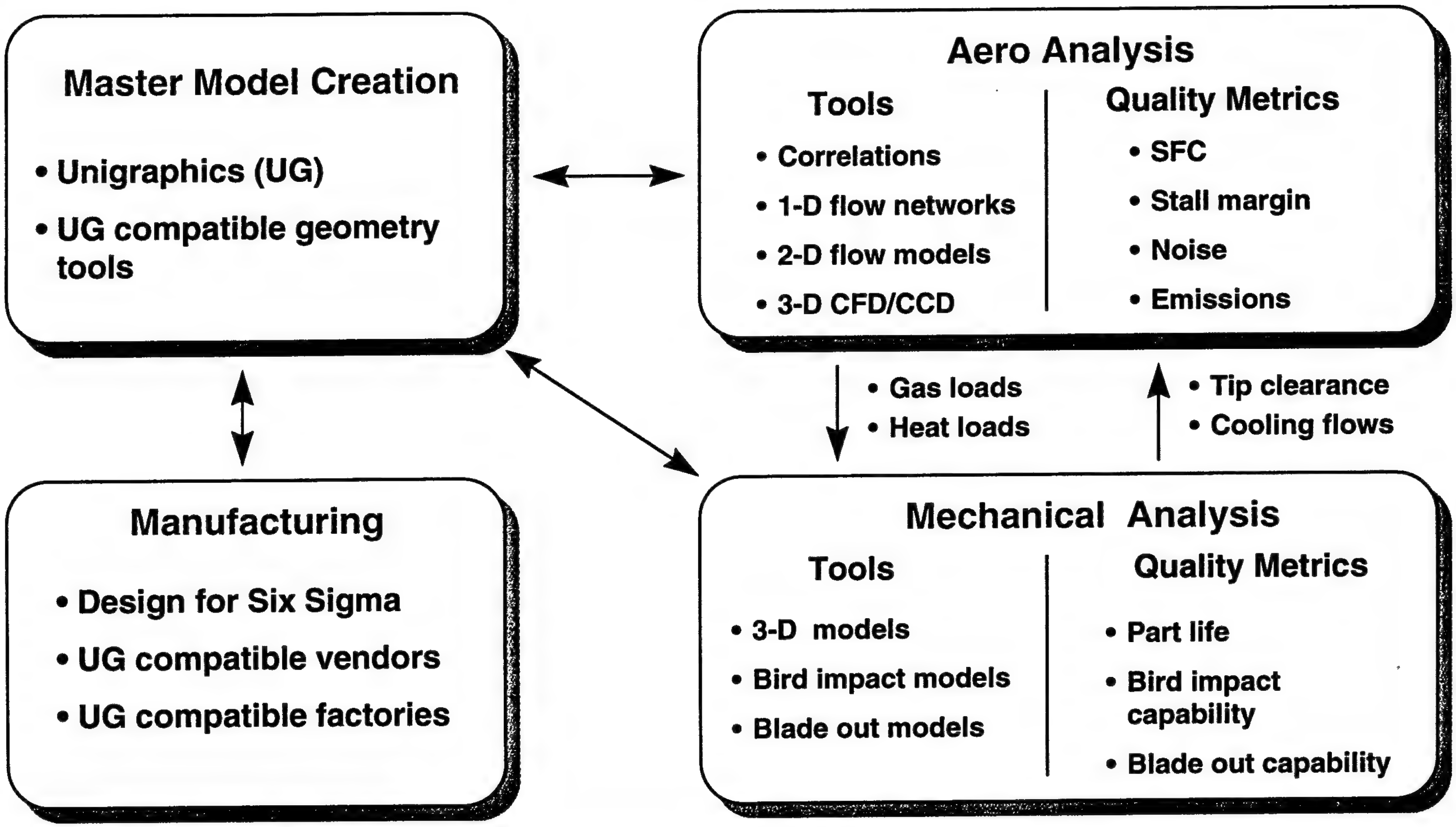
Enhances Fighter Aircraft Agility and Combat Effectiveness

Product Creation Thruput Strategy

- All technologies to be proven prior to launch
- Must achieve all targets during pre-launch (weight, cost, schedule)
- Must identify all partners, all suppliers during pre-launch activities
- Do not start detail design until **ALL** requirements are established, i.e., technical and program
- All hardware for certification program identical.
- Program to be focused on certification
- Risk Management plans to cover key program contingencies

Requirements need to be absolutely firm before deploying significant levels of resources

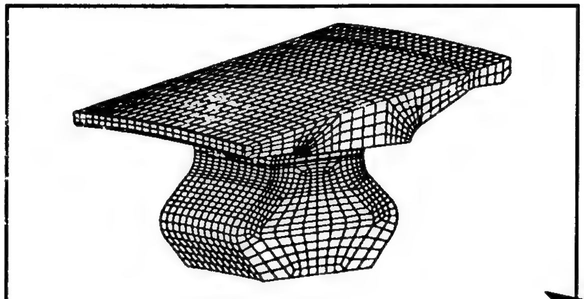
Integrated Engineering and Manufacturing



Common geometry enables 24-Month Product Creation with improved quality

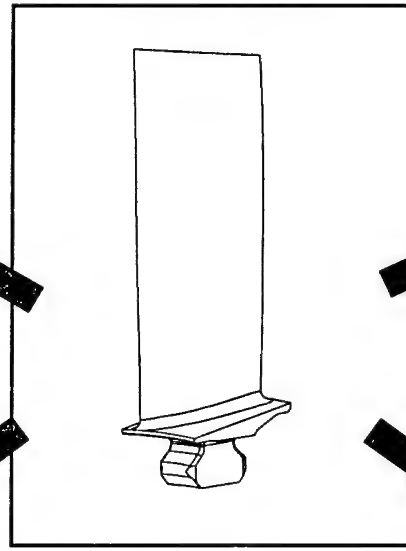
Fan and Compressor Design

Parametric Dovetail Modeling

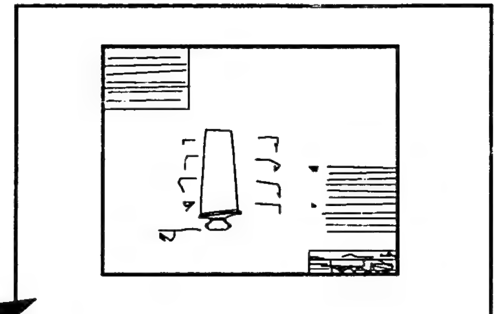


- Automated Meshing
- Standardization of Dovetail Designs
- Cycle Time: 9 Days to 6 Hours

Unigraphics Master Model

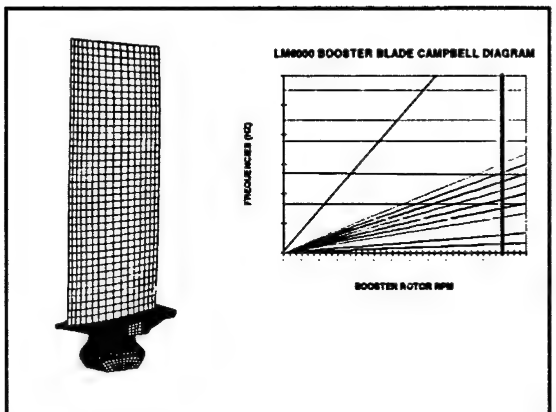


Template Drawings



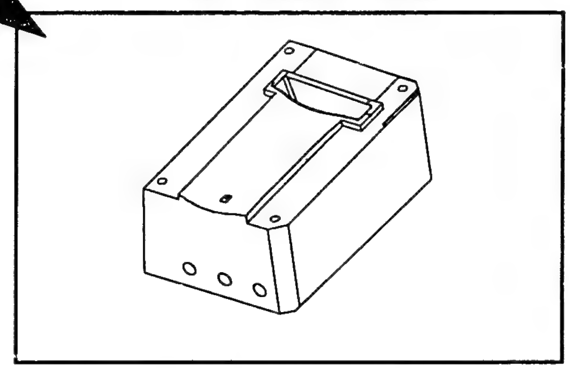
- Standardization of Notes and Processes
- Cycle Time Reduction: 3 Weeks (Est.)

Automated Analysis



- Full Blade Analysis Concurrent With Design
- Automated Boundary Condition and Load Application
- Standardized Analysis Approach
- Cycle Time: 2+ Days to <1 Day

UG Tooling Design/Inspection

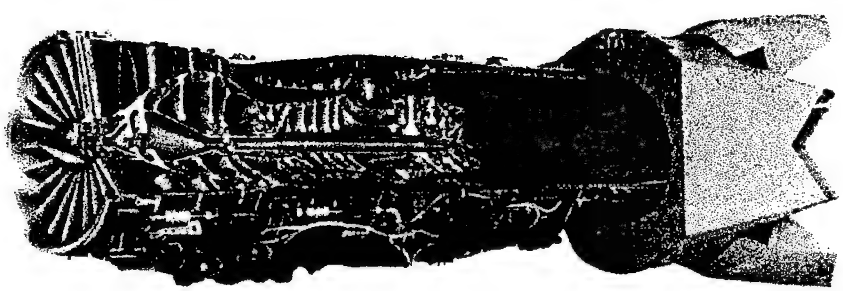


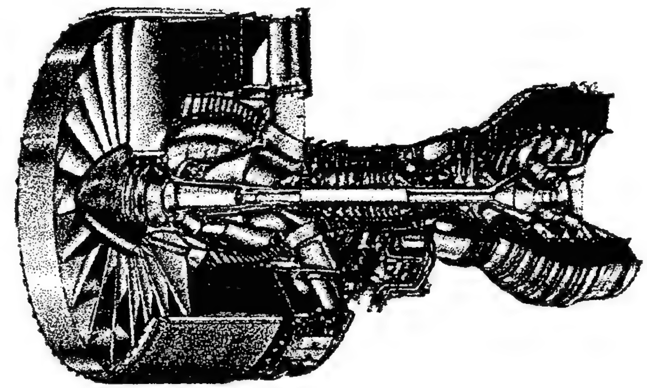
- Cycle Time Reduction: ~10 Days
- Improved Quality - Driven by Engineering Master Model

Summary

- Lots of challenges and lots of opportunities
- Development costs and acquisition costs are becoming major focus in product definition and selection
- Keys to success reside in our ability to create new products with:
  - An orderly process
  - Improved design tools
  - Properly focused technologies

IMPACT OF MODELING AND DIAGNOSTIC TECHNOLOGIES ON THE OPERATING COST OF AIRCRAFT GAS TURBINE ENGINES

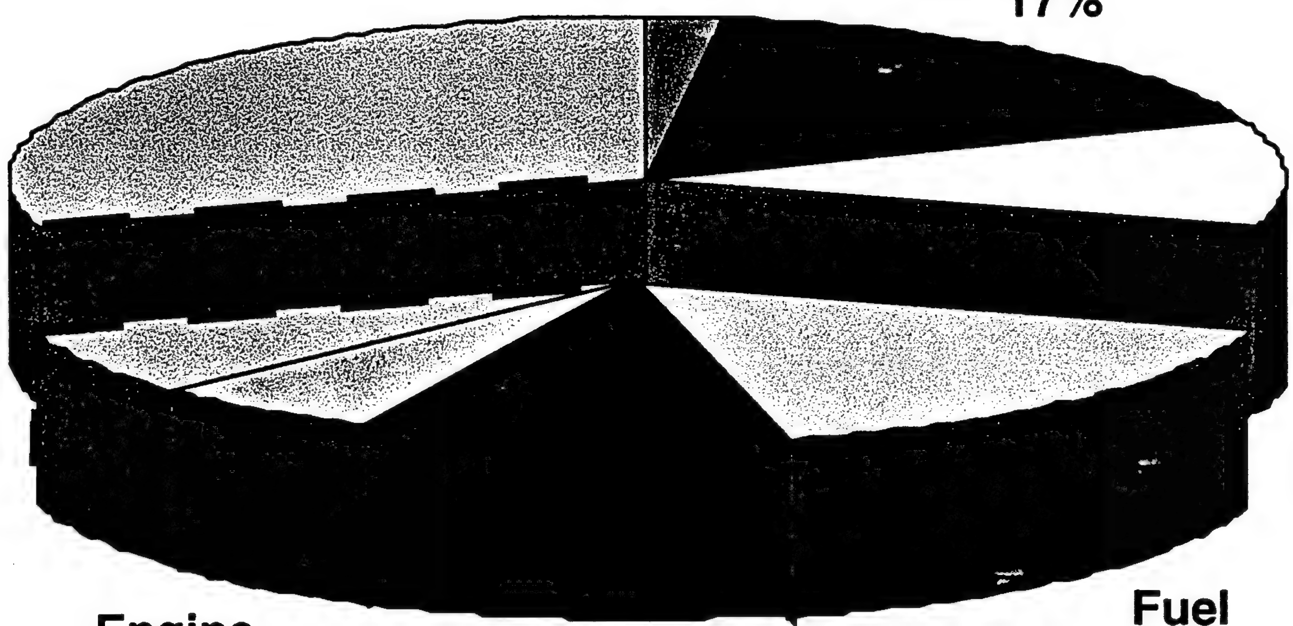




Lee Coons
Vice President Engineering
15 June 1998

COST ELEMENTS FOR AIR TRANSPORTATION

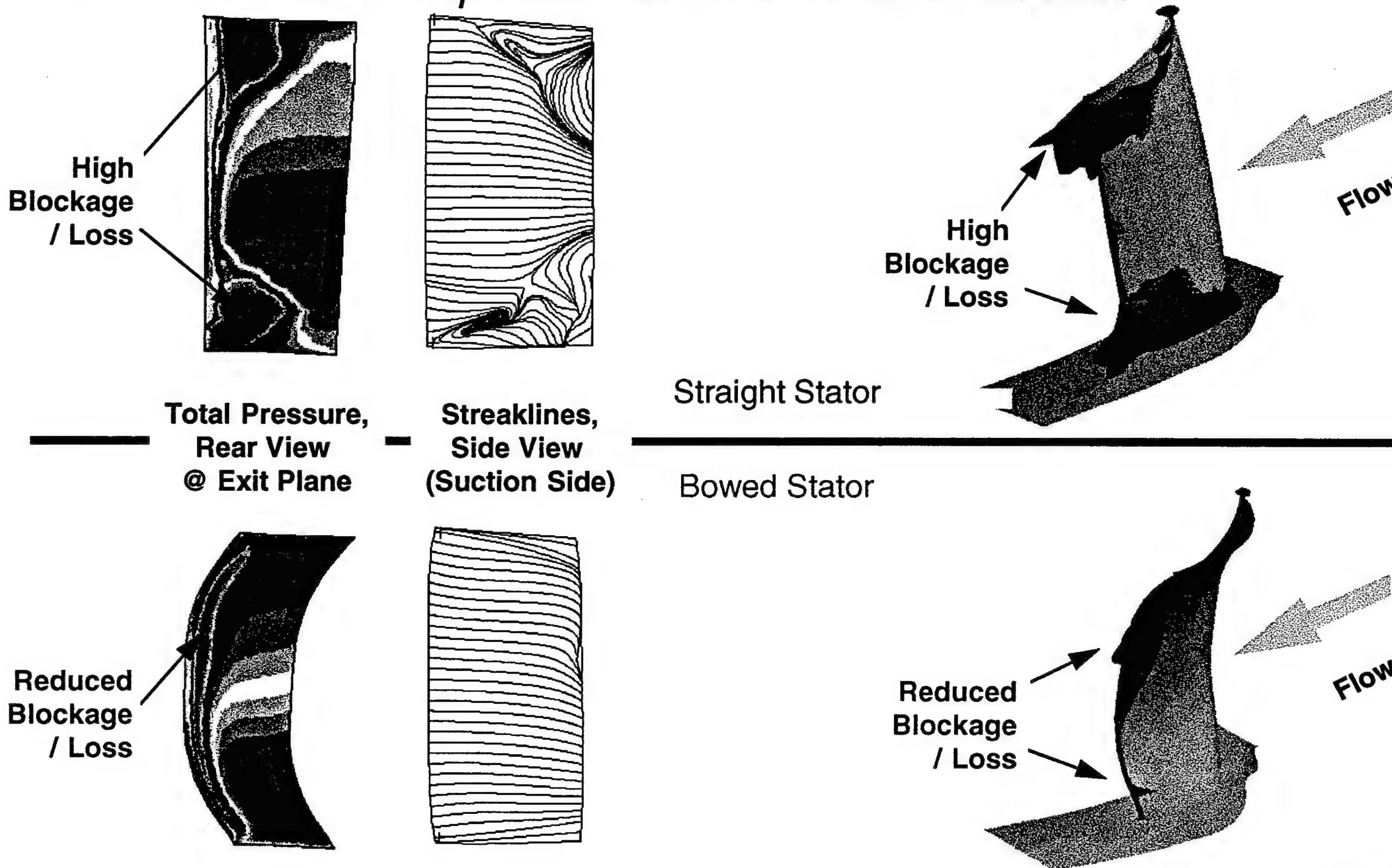
Gas Turbine Engines Influence ~ 40% of Total Cost



Utilization = 9.4 hrs/day
125 seat airliner

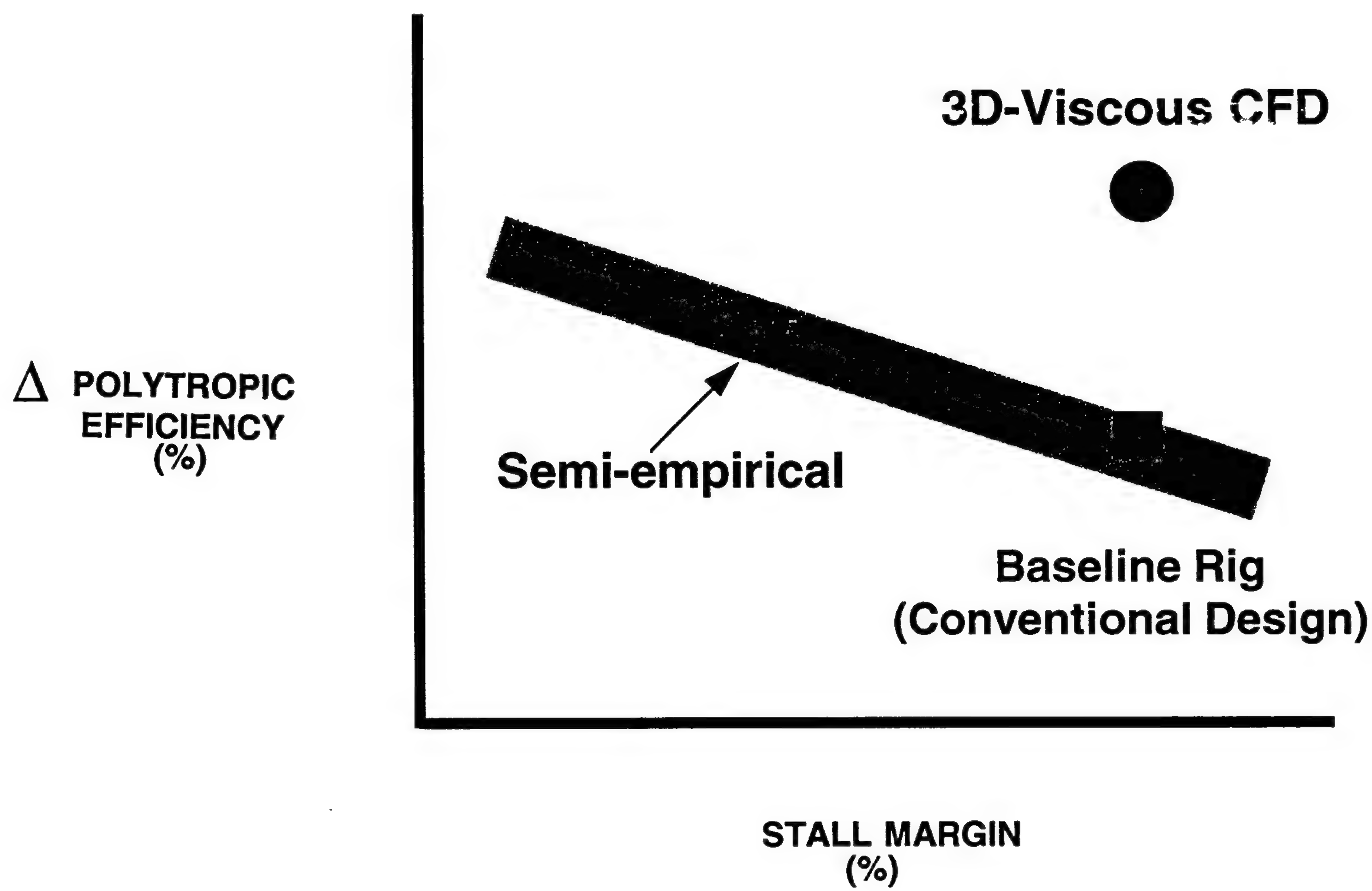
IMPROVED (PHYSICS BASED) MODELS FOR ENHANCED PERFORMANCE

Bowed Compressor Stators Reduce Losses



IMPACT OF (PHYSICS BASED) MODELING

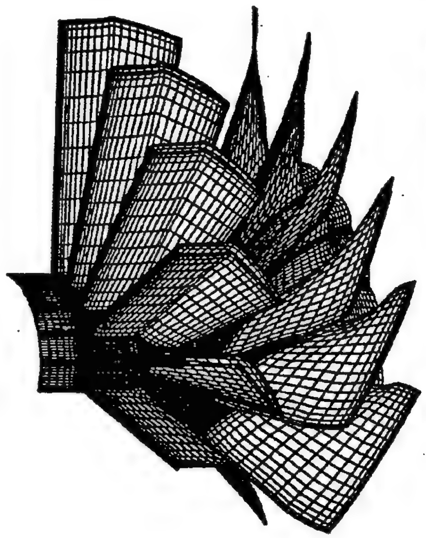
Improved Compressor Performance (Reduced Fuel Burn)



IMPROVED AEROELASTIC ANALYSIS TOOLS

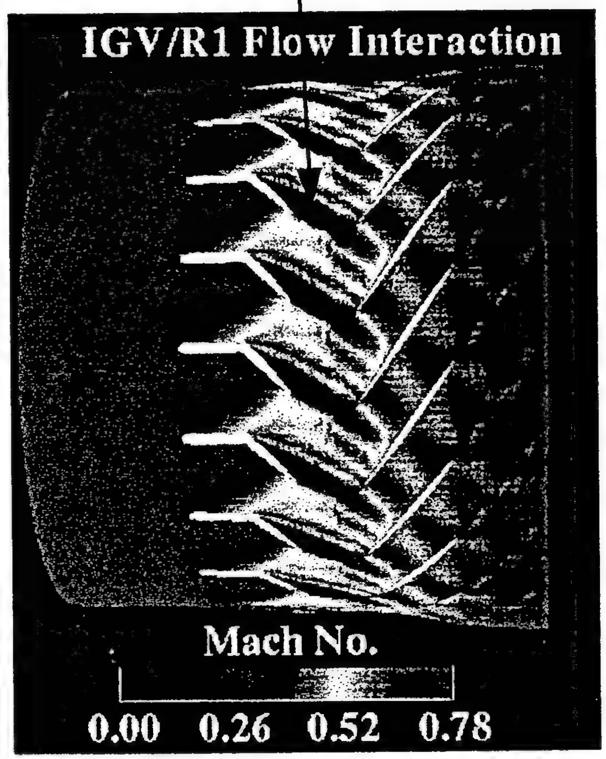
FLARES Model Used to Eliminate Fan Blade Structural Concern

Flow



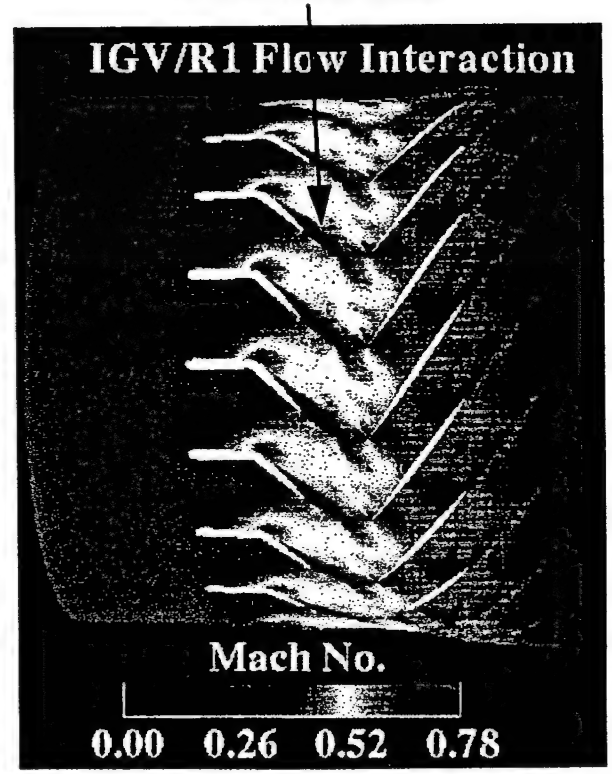
IGV and
1st Blade

Separation



Baseline

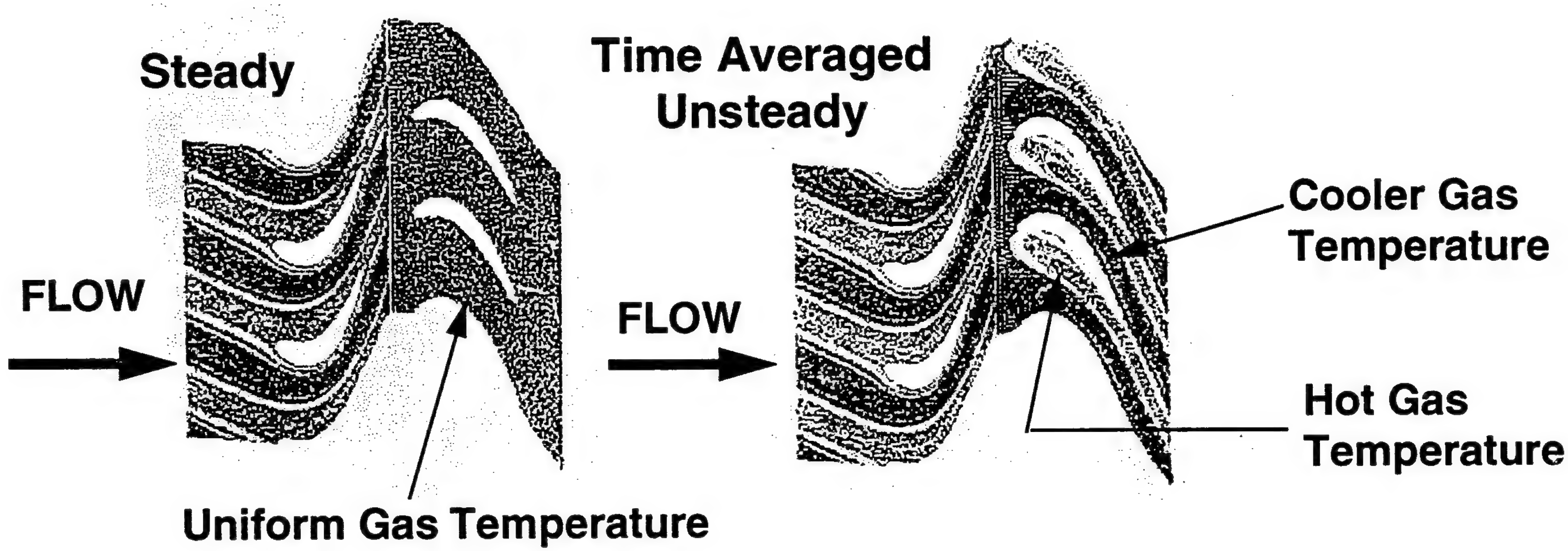
Separation
Eliminated



Redesign

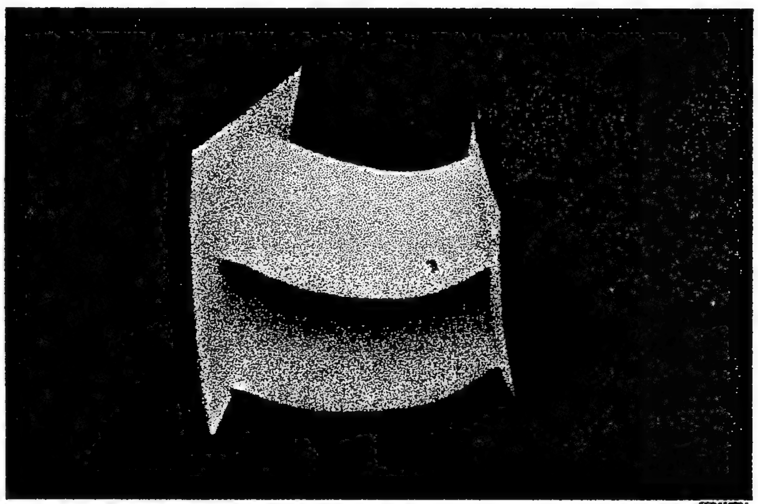
IMPROVED (PHYSICS BASED) MODELS FOR ENHANCED CAPABILITY

Unsteady Flow Simulation Captures More Realistic Aero/Thermal Environment

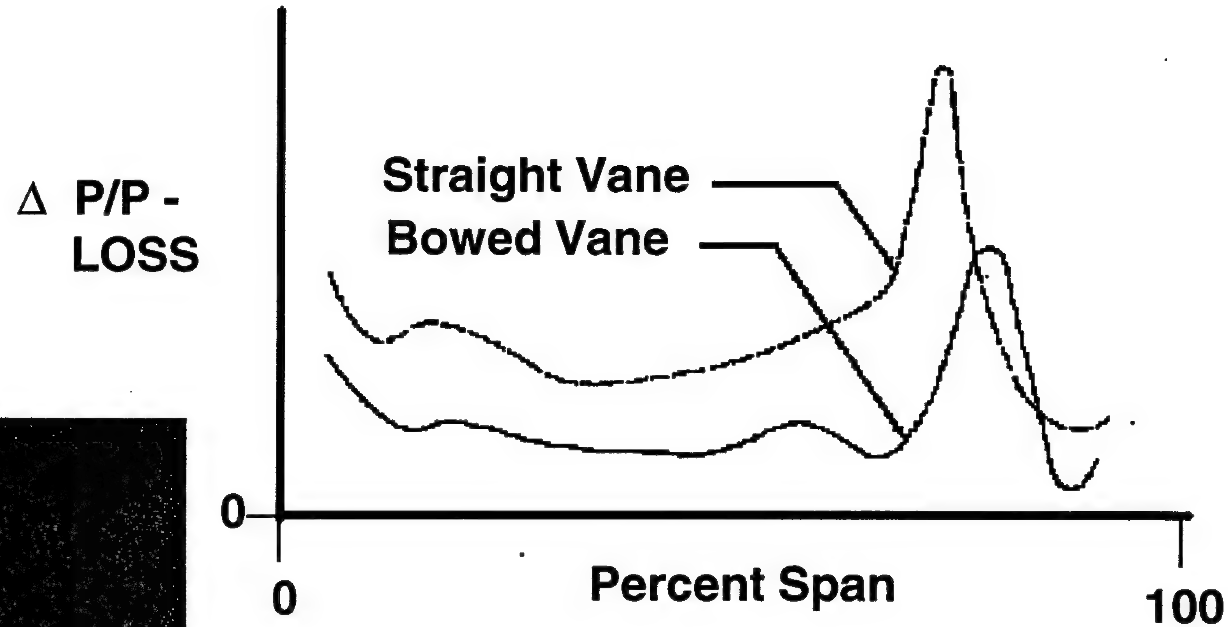


IMPROVED (PHYSICS BASED) MODELS FOR ENHANCED PERFORMANCE

Advanced Turbine Aerodynamics Improves Performance

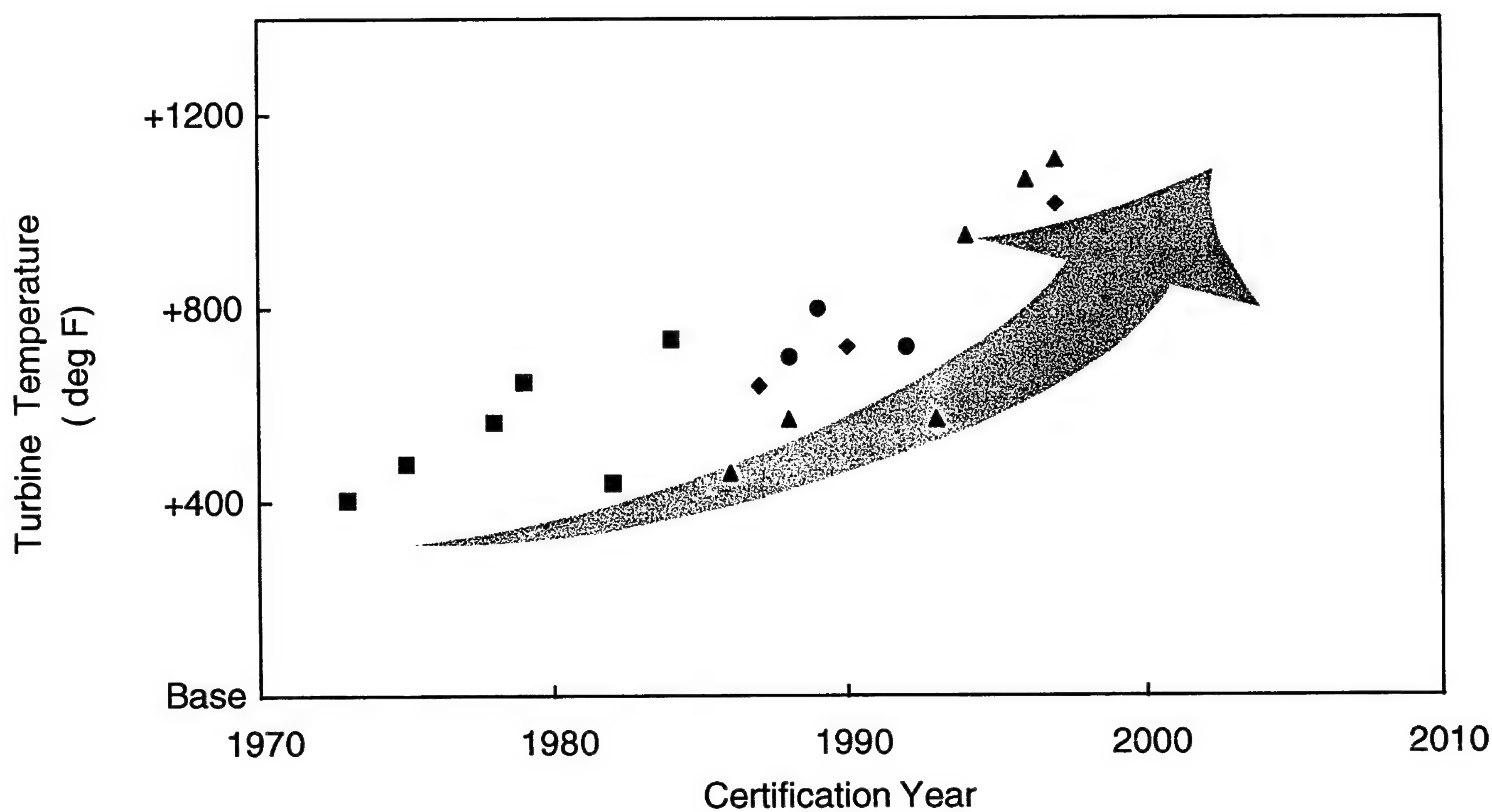


2nd Turbine Vane



TURBINE TEMPERATURE CHALLENGE

Higher Turbine Temperatures Required to Increase Efficiency and Decrease Weight (range, performance)



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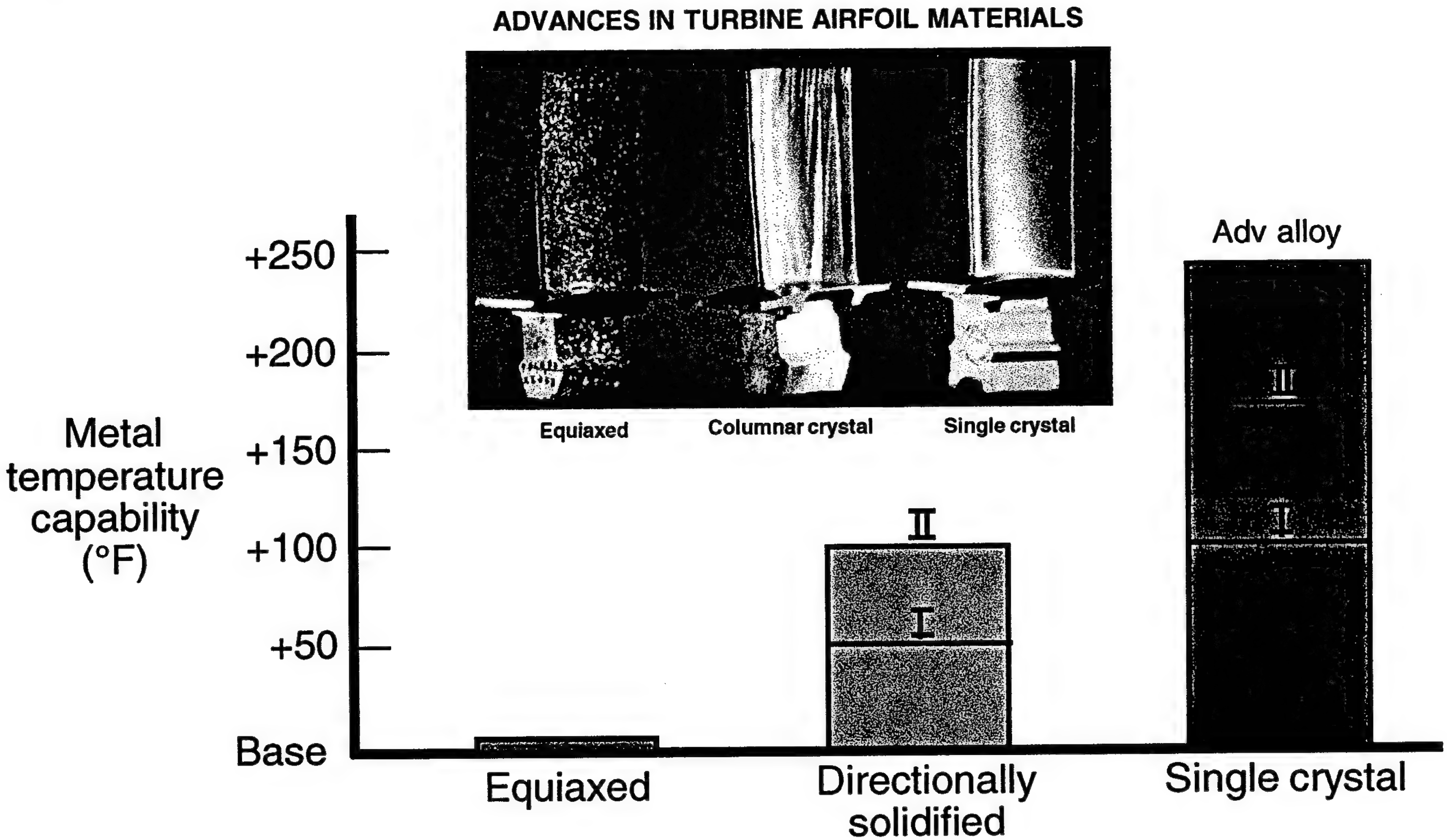
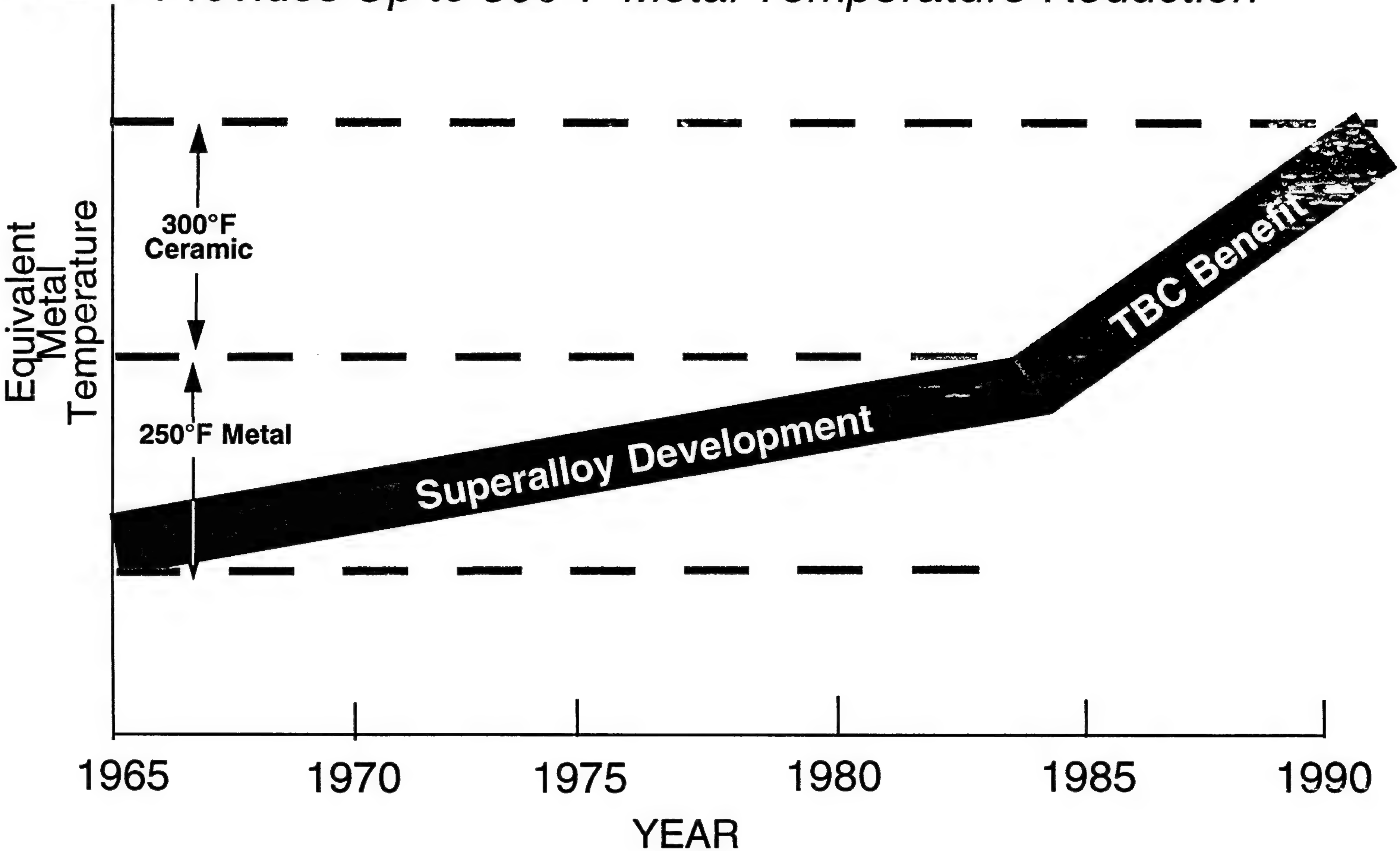
TURBINE BLADE MATERIALS EVOLUTION

Improved Materials Addresses Part of the Challenge



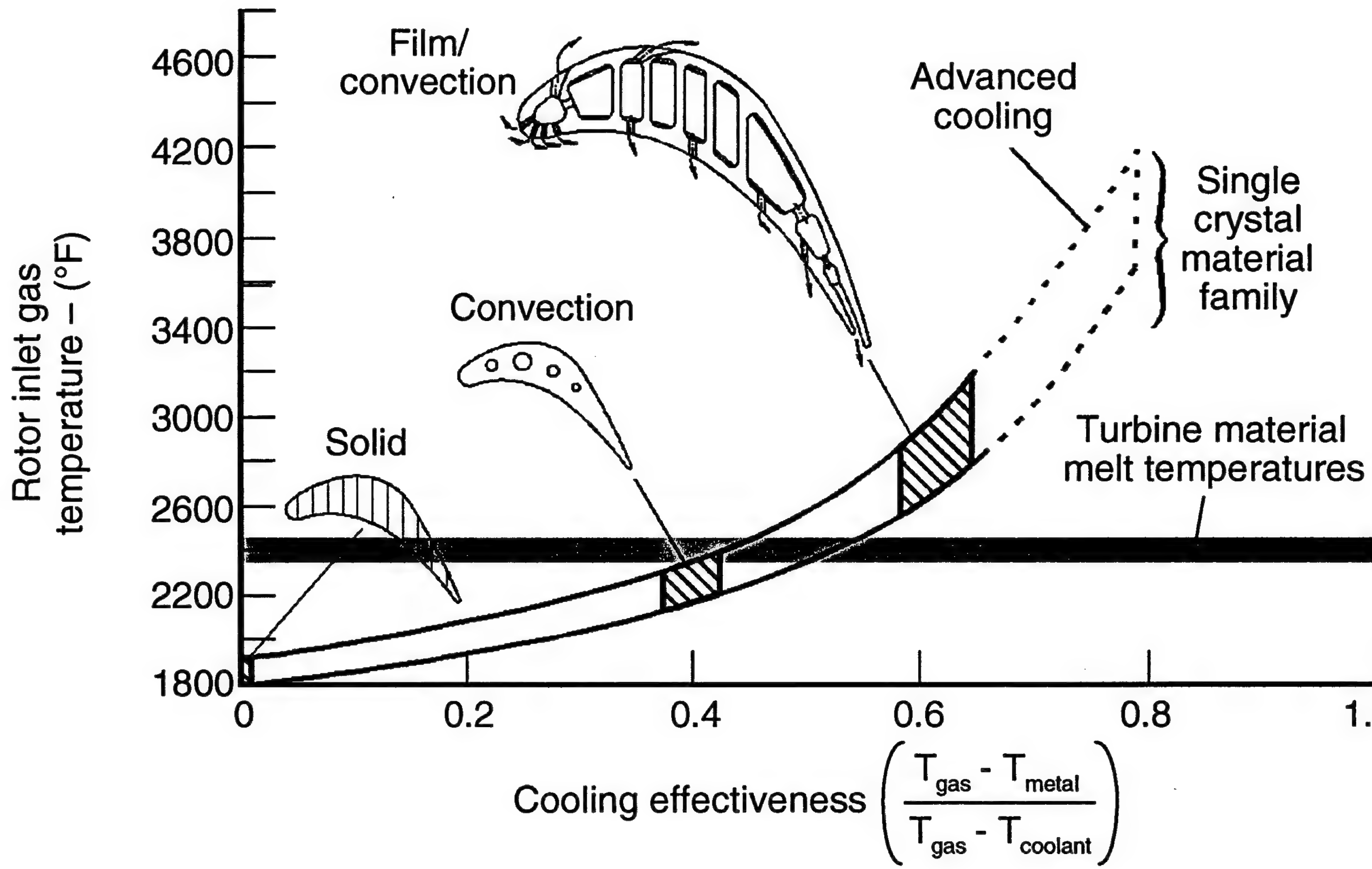
THERMAL BARRIER COATING

Provides Up to 300°F Metal Temperature Reduction

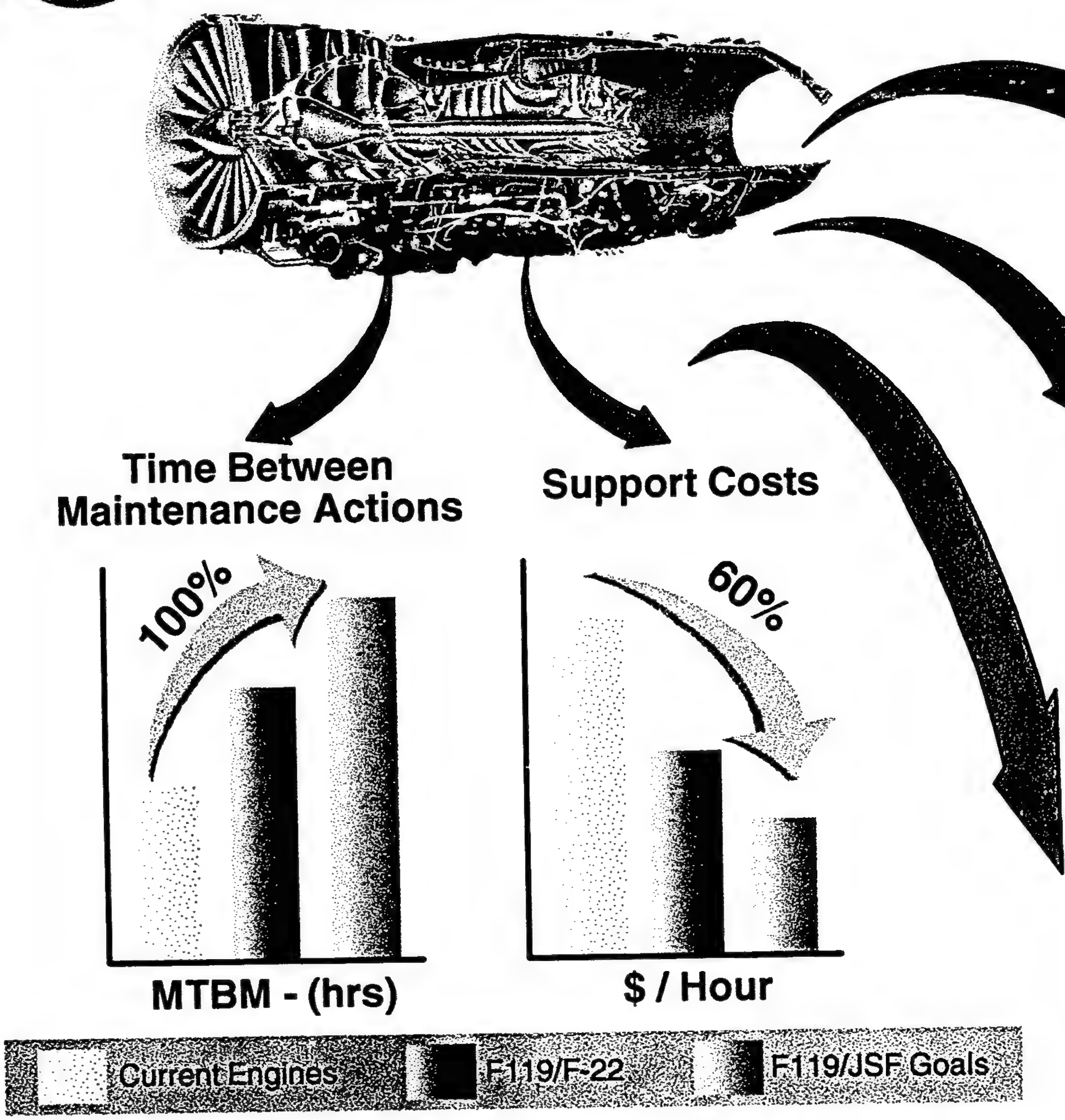


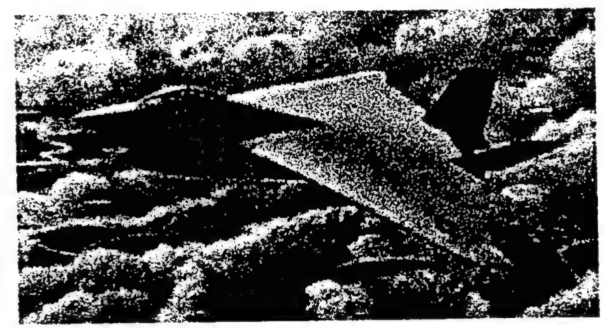
TURBINE COOLING TECHNOLOGY

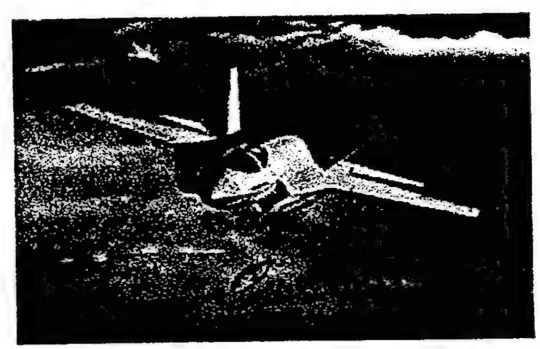
Operating Over 800°F Above the Material Melting Point



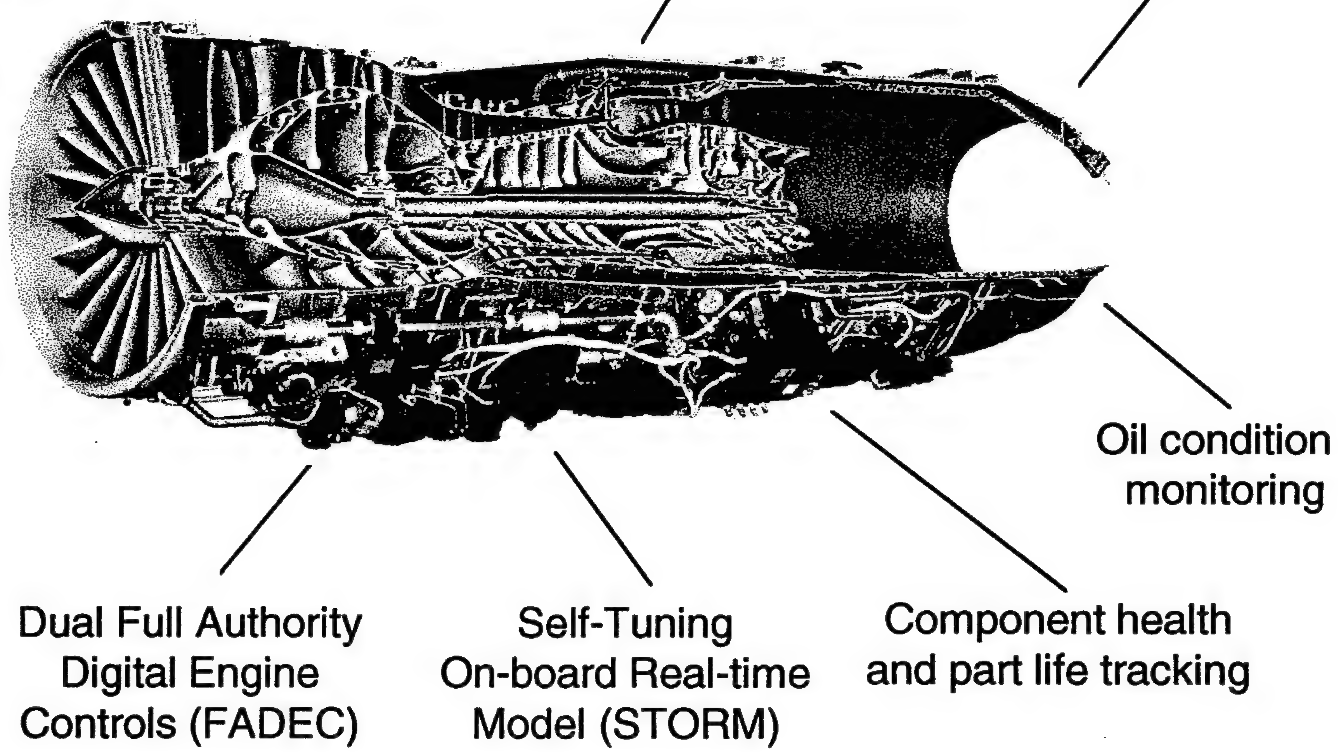
F119 MAINTENANCE FEATURES REDUCED SUPPORT COST



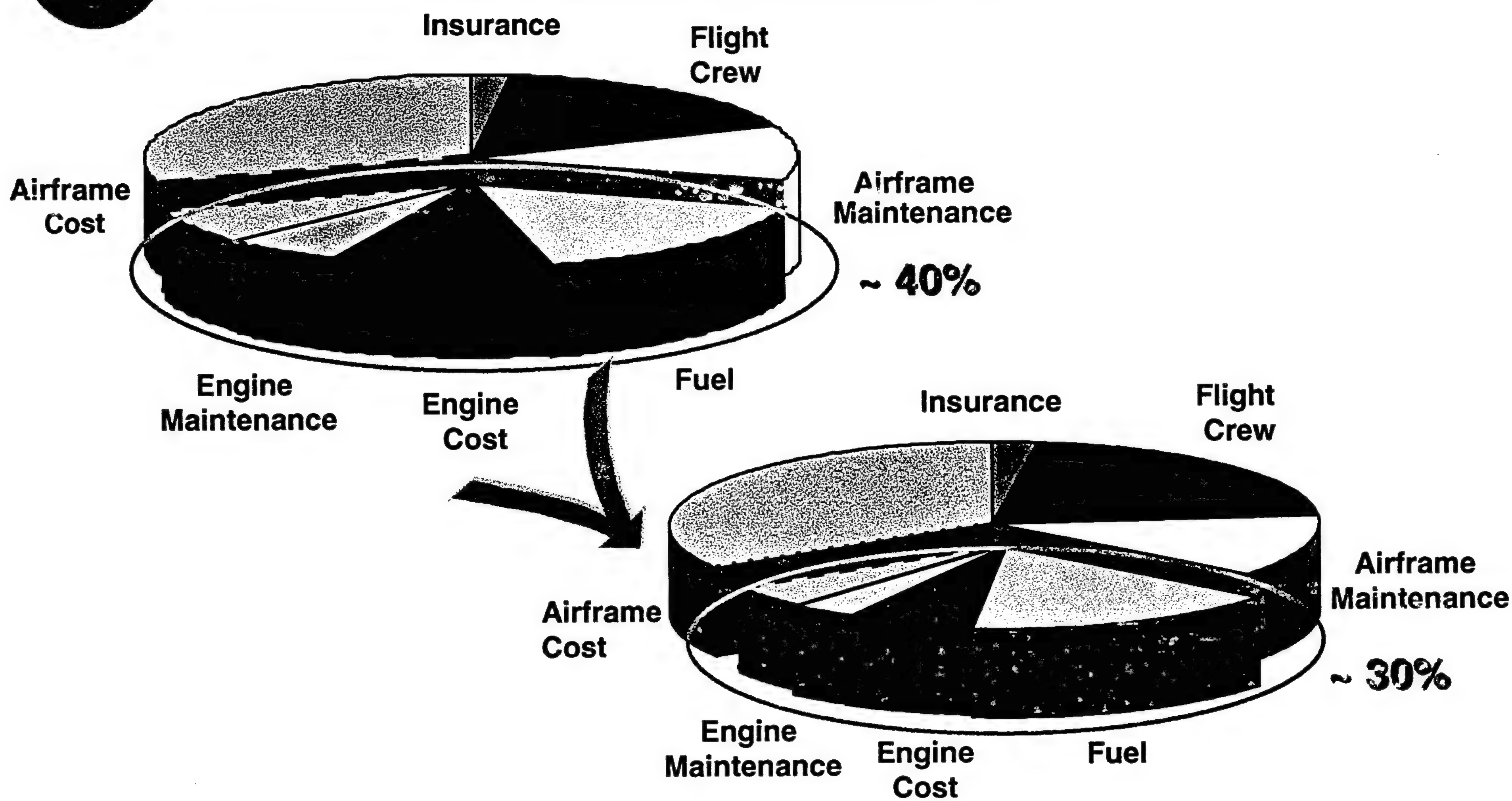




JSF DIAGNOSTICS / PROGNOSTICS



SUMMARY



Improved Modeling, Technology and Diagnostics = Reduced Cost of Ownership and Improved Customer Value.

Allison

Technology Challenges for 21st Century Gas Turbine Engines

Bob Fagan

Chief, Compression Systems

Allison Engine Company

Edited Version for Publication

Rolls-Royce

Allison

Technology Challenges for 21st Century Gas Turbine Engines

TECHNOLOGY DRIVERS

- Military (AADC)
  - Provide Global Reach
  - Project and Sustain Global Power
  - Flexible, Reliable, Survivable, Affordable

- Commercial (AEC)
  - Cost (Acquisition, Operations)
  - Predictability of Engine Maintenance
  - Regulatory (Environmental)
  - Safety

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Technology Challenges for 21st Century Gas Turbine Engines

EVENTS WHICH WOULD IMPACT TECHNOLOGY DEVELOPMENT ACTIVITIES IN THE GAS TURBINE INDUSTRY

- **Unanticipated Change in Environmental Regulations**
- **Adverse Public Response to a Real or Perceived Passenger Safety Issue**
- **Change in World Economics**
- **Outbreak of Hostilities Between World Powers**

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Technology Challenges for 21st Century Gas Turbine Engines

BUSINESS ASPECTS OF TECHNOLOGY DEVELOPMENT

- Historically, governments have played a key role in technology development for gas turbine engines.
- Cost to develop and certify a single new engine is a huge financial investment for even the largest companies.
  - Factor in the "strategic partnerships" between competing companies on a number of engine programs
- Cost to maintain world-class capabilities in the technologies required for competence in the gas turbine industry is large.
  - Factor in the consolidation of the gas turbine industry
- Tendency in the industry to pay the cost to develop technology that is nearly identical numerous times.
- **Customer demands continual advancement in technology of our products at lower cost**

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Technology Challenges for 21st Century Gas Turbine Engines

APPROACH TO REDUCE COST OF TECHNOLOGY DEVELOPMENT

Define pre-competitive technologies
- Materials systems development
- Cycle analysis methodologies

Cooperative technology development
- Cost savings to individual companies
- Cost savings to regulatory agencies

Focus company efforts on differentiating capabilities
- Design methodology / Engine configuration
- Manufacturing capability
- Product support

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Technology Challenges for 21st Century Gas Turbine Engines

CRITICAL GAS TURBINE ENGINE TECHNOLOGIES

- Design / Configuration
- Materials / Manufacturing Technology
- Combustion
- Controls/Diagnostics
- Aerodynamics (Performance, Acoustics)
- Cooling Systems

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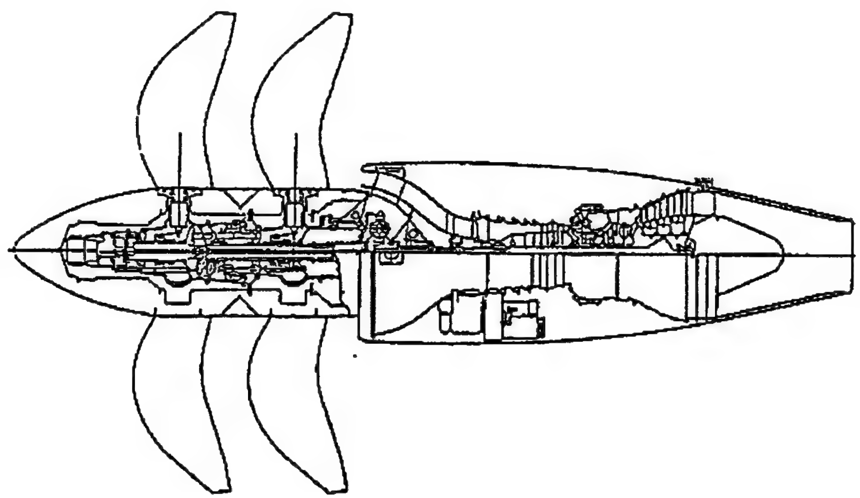
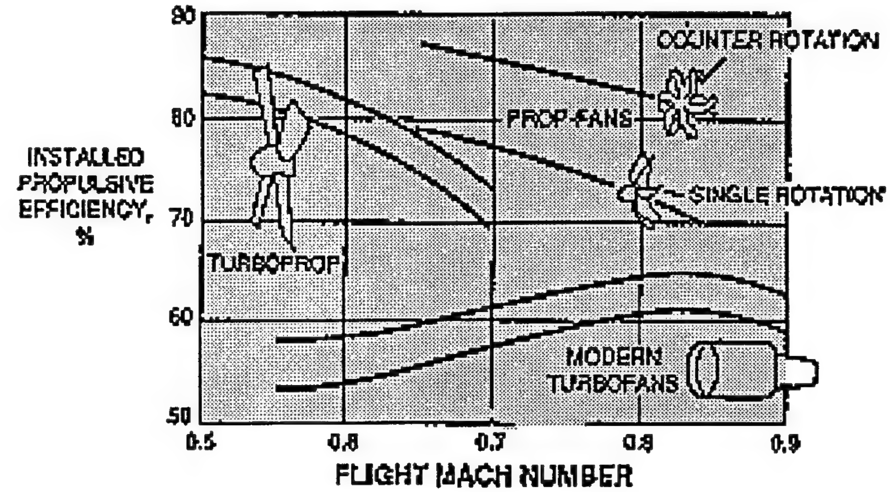
Technology Challenges for 21st Century Gas Turbine Engines

PROPFANS PROVIDE HIGH PROPULSIVE EFFICIENCY





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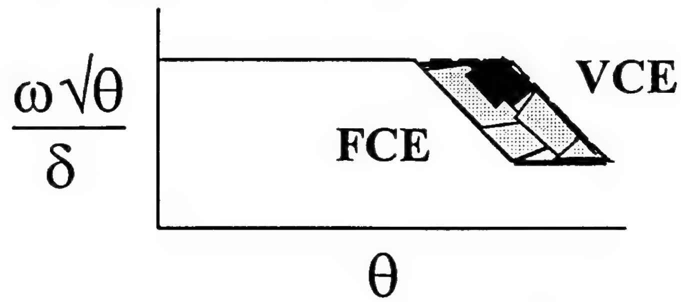
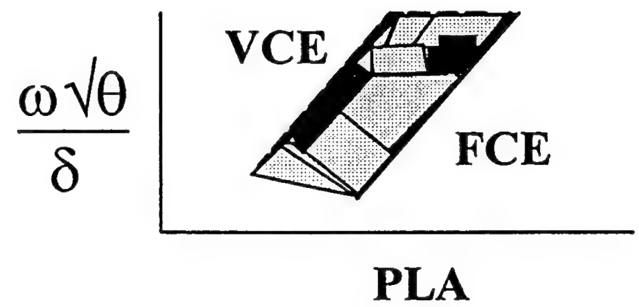
Technology Challenges for 21st Century Gas Turbine Engines

VARIABLE CYCLE ENGINES FOR LONG RANGE AIRCRAFT

- Improved Engine - Inlet airflow matching

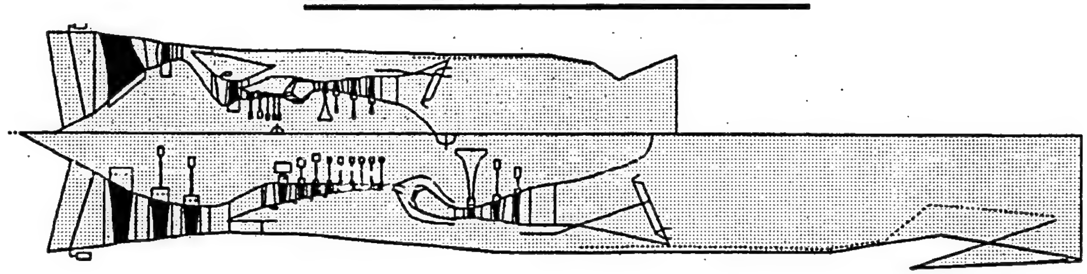


- Improved Installed SFC



- Fixed A8/A9 Fluidic Nozzle

IHPTET VCE Turbofan



Today's FCE Turbofan

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Technology Challenges for 21st Century Gas Turbine Engines

MORE ELECTRIC ENGINE DEVELOPMENT

Timetable

- First Application in 2005 - Industrial
- IHPTET Demonstrations 2002-2005
- Flight Engine Application 2010-2012
- Control Optimization/Prognostics 2015 - 2020

Payoffs

- 10% Engine Weight Reduction
- 90% Bearing loss Reduction
- Elimination of recirculating lube system, AGB, and PTO shaft
- Performance Improvements (Stability Control, Clearance Control)
- Health Monitoring/Maintenance on Need/Planned

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Technology Challenges for 21st Century Gas Turbine Engines

HIGH TEMPERATURE FAULT TOLERANT MAGNETIC BEARINGS AND ISG

- Auxiliary Bearing Design/ Lubrication (Once Through)
- High Temperature Rotor Damping
- High Temperature Sensors
- High Strength Material/ Constructions for Thrust Disk
- High Temperature Winding
- System and Dynamic Simulation Tools
- Integration of All Mechanical/ Electrical Components
  - ISG and AMB forces
  - Auto Tuning Controller
  - Full Scale Demonstration

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Technology Challenges for 21st Century Gas Turbine Engines

FAN MATERIALS

CURRENT

•Solid Titanium

•NEAR TERM

•Hollow Titanium

•OMC's

•FAR TERM

•Berylium Aluminum

•Aluminum and Magnesium MMC's

COMPRESSOR MATERIALS

CURRENT

•Titanium Attached Blades

NEAR TERM

•Advanced Titanium

•Orthorhombic Titanium Aluminides

•Titanium and Nickel Blisks

FAR TERM

•Titanium MMC Blings

•Improved Orthorhombic Titanium Aluminides and Nickel Alloys

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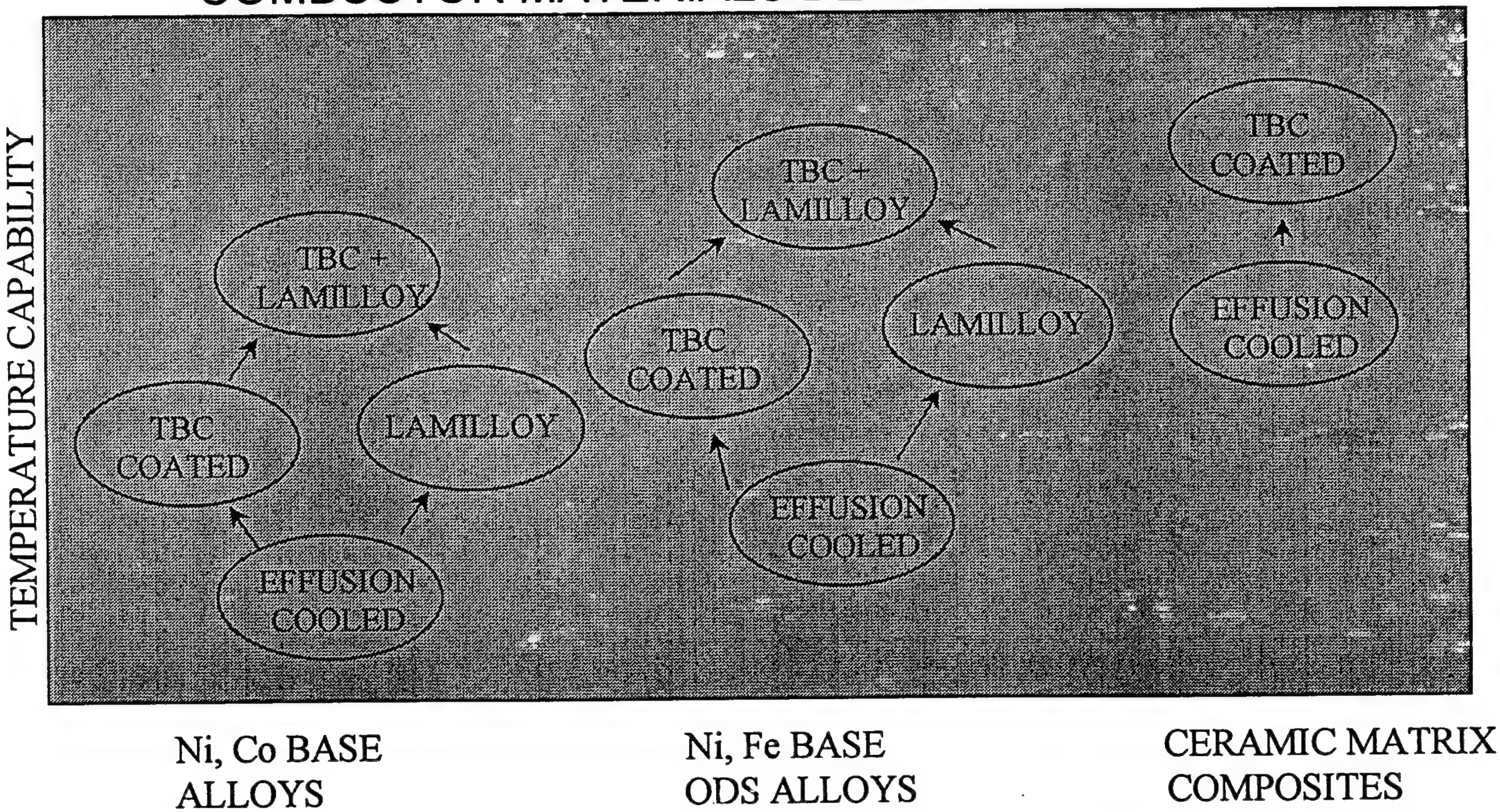
Technology Challenges for 21st Century Gas Turbine Engines

COMBUSTOR MATERIALS DEVELOPMENT



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Technology Challenges for 21st Century Gas Turbine Engines

TURBINE MATERIALS DEVELOPMENT

CURRENT

- 2nd - 3rd Generation Single Crystal Airfoils
- TBC - Vanes
- Nickel Disks

NEAR TERM

- 3rd - 4th Generation Single Crystal Airfoils
- TBC - Blades
- Improved Nickel Alloys

FAR TERM

- Intermetallic Blades
- Prime Reliant TBC
- Intermetallic Disks

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Technology Challenges for 21st Century Gas Turbine Engines

Low Cost Combustors
- Advanced liner structures
- Low cost materials
- Low cost manufacturing
- Reduced part count
- Increased maintainablity

Advanced Design Methods
- Advanced numerics
- Reduced reaction scheme
- Increased computing power

High Temperature Rise
- Advanced fuel injectors
- Advanced cooling
- High temperature metallics
- Ceramics

Aircraft	CAEP 2	CAEP 4	Cruise and Climb Emissions Limits
Industrial	25 ppm NOx	15 ppm NOx	9 ppm NOx

2000 2005 2010 2015 2020 2025

High Temperature Fuel Systems
- High stability fuels
- Antideposition coatings
- Supercritical fuel systems
- Integrated thermal management

Low Emissions
- Advanced fuel mixers
- Advance cooling
- Novel configurations
  - variable geometry
  - fuel staging

High Performance Combustor
- Integrated combustor diffuser
- High performance diffuser
- Active controls

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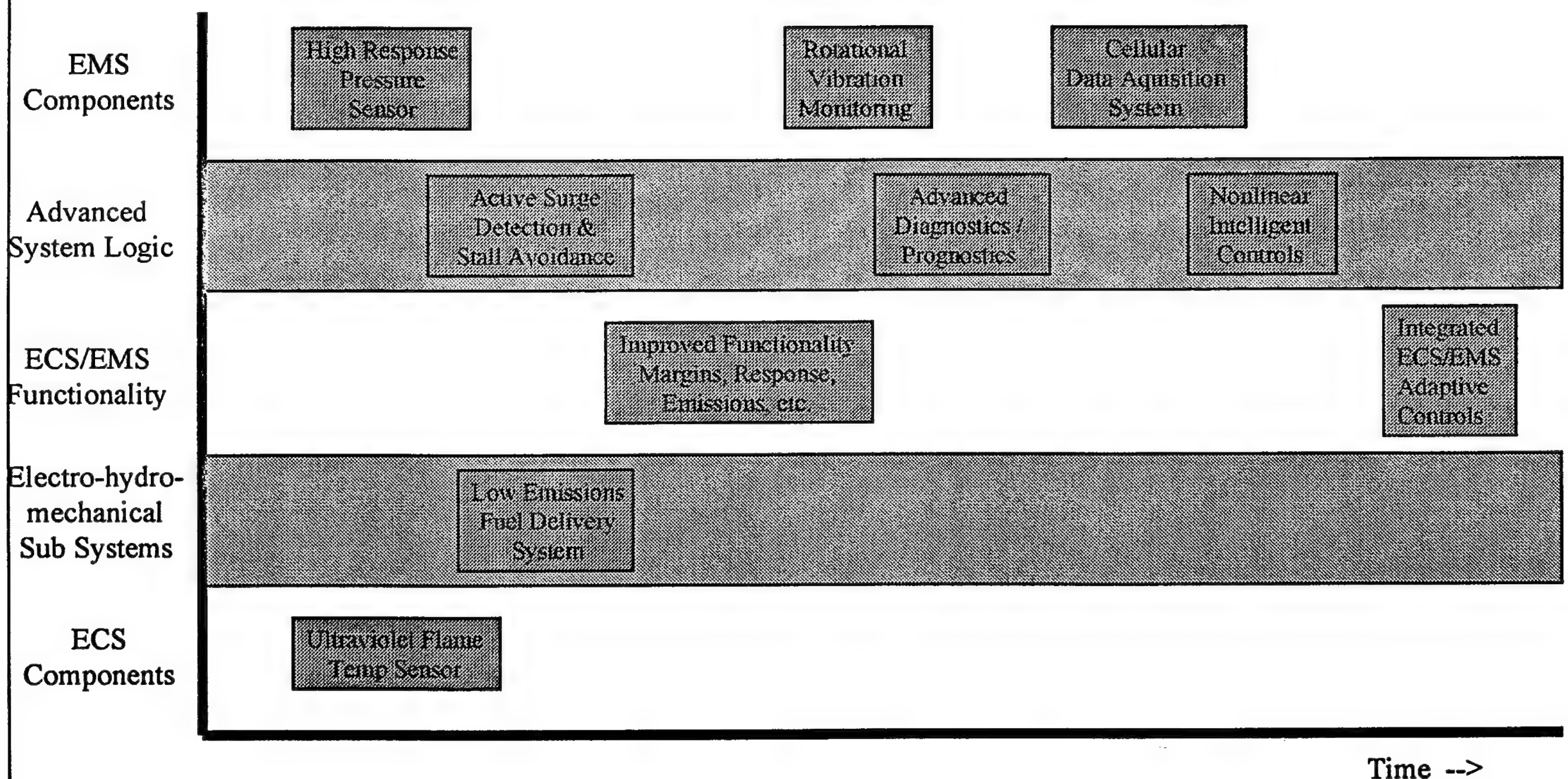
Technology Challenges for 21st Century Gas Turbine Engines

ADVANCED CONTROLS ROAD MAP



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Technology Challenges for 21st Century Gas Turbine Engines

ROTATIONAL VIBRATION MONITORING

- Sense Torsional Vibration of Rotating Parts
- Characterize “Good” Vibration Signature
- Determine Signal Amplitude and Frequency
- Sensitivity to Blade and Disc Cracks
- Inject Faults, Run Engine, Take Data
- Correlate Signal to Known Faults
- Develop Prognostic Algorithms

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Technology Challenges for 21st Century Gas Turbine Engines

AIRCRAFT NOISE ISSUES

- Community noise levels in the vicinity of airports represent a growth barrier for commercial aviation.
  - Certification noise levels for aircraft will become more restrictive
  - Results in a proliferation of local regulations
- Significant reductions in engine noise using current practices leads to oversize, derated powerplants.
- Other technology areas have potential for negative impact upon noise.
- Economically viable approaches to low noise engine will involve fundamental change to engine cycle and component architecture.

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Technology Challenges for 21st Century Gas Turbine Engines

Forward Swept Fan
•Reduced “Buzzsaw” tones - shock retention
•Reduced BPF tones - increased R-S spacing
•Requires high strength, low density material
•EIS - 2005

Optimized Forced Mixer
•Reduced jet mixing noise
•EIS - 2000

Improved Acoustic Liner
•Wider bandwidth
•Optimum placement
•Active/adaptive control
•EIS - passive: 2005
• - active:2015

Reduced Airfoil Count Swept OGV
•Reduced BPF tones
•Reduced Fan broadband noise - reduced vane count
•EIS - 2005

Alternate Cycles
•UHBR, Geared Fans
•Eliminate jet noise,minimize fan noise
•Requires advanced materials, lightweight gear systems
•EIS - 2015-2020

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Technology Challenges for 21st Century Gas Turbine Engines

PREDICTABILITY

COST

SAFETY

AFFORDABLE

FLEXIBLE

SURVIVABLE

REGULATORY

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Challenges of Advanced Technology in Military Applications

Georgia Tech June 15, 1998

by John G. Meier

Agenda

- IHPTET/Joint Turbine Advanced Gas Generator (JTAGG) Program
- IHPTET technology transition in:
  - T55 for CH47 growth
  - T800 for Comanche growth
  - AS3000 helicopter engine for T700 replacement in Apache, Blackhawk, and Seahawk
  - UCAV application
- Challenges

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Government and Industry Integrated High Performance Turbine Engine Technology Initiative

G7475-1

	Phase I (1991)	Phase II (1997)	Phase III (2003)
JTAGG	**Turboshaft/Turboprop Goals**		
SFC	-20%	-30%	-40%
shp/wt	+40%	+80%	+120%
Production Cost	-	-20%	-35%
Maintenance Cost	-	-20%	-35%
JETEC	**Limited Life UAV Propulsion Goals**		
TSFC	-20%	-30%	-40%
Cost	-30%	-45%	-60%

Reference Donald M. Dix, 11/96

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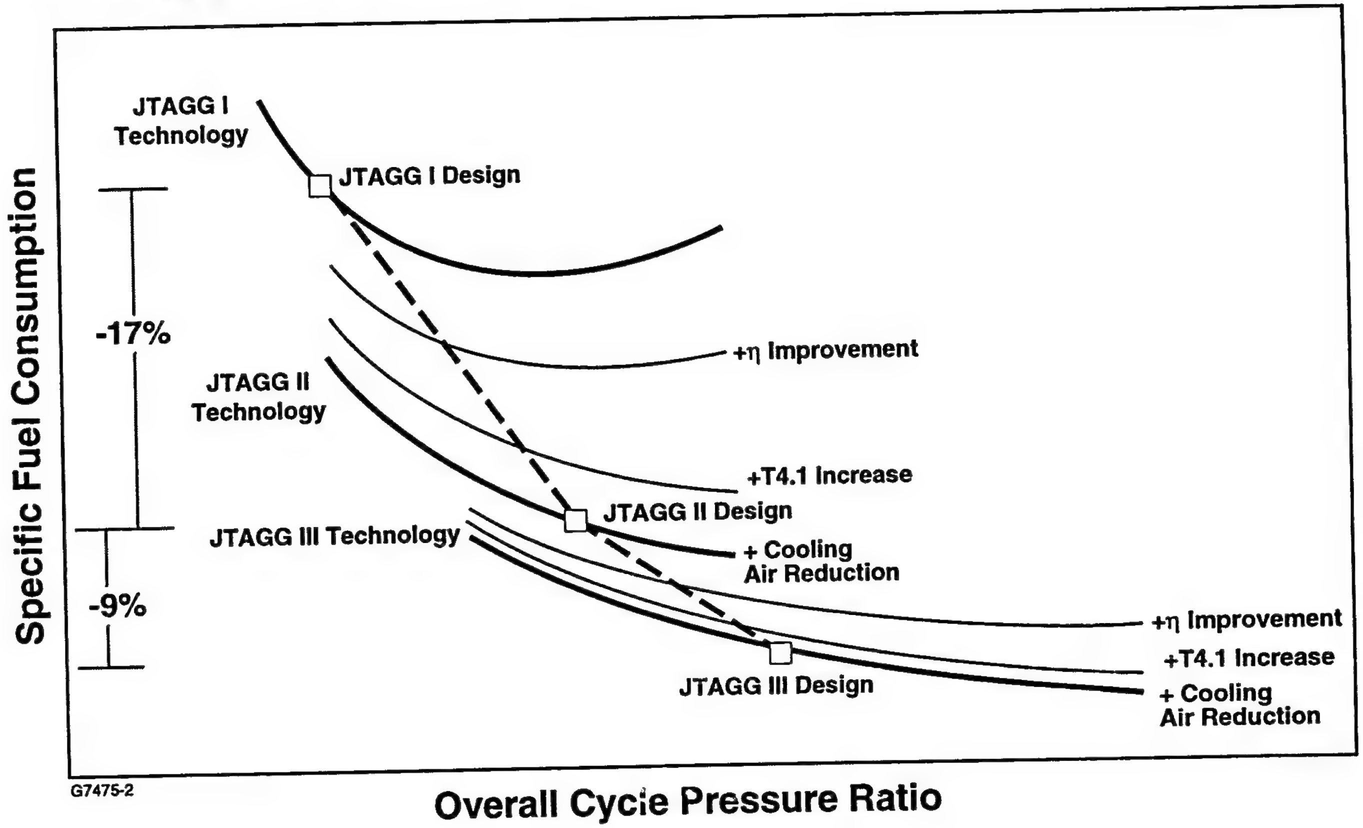
Cycle, Pressure Ratio, and Temperature Technology for Fuel Burn



Combination of higher PR, $T_{4.1}$, and η required to achieve SFC goals

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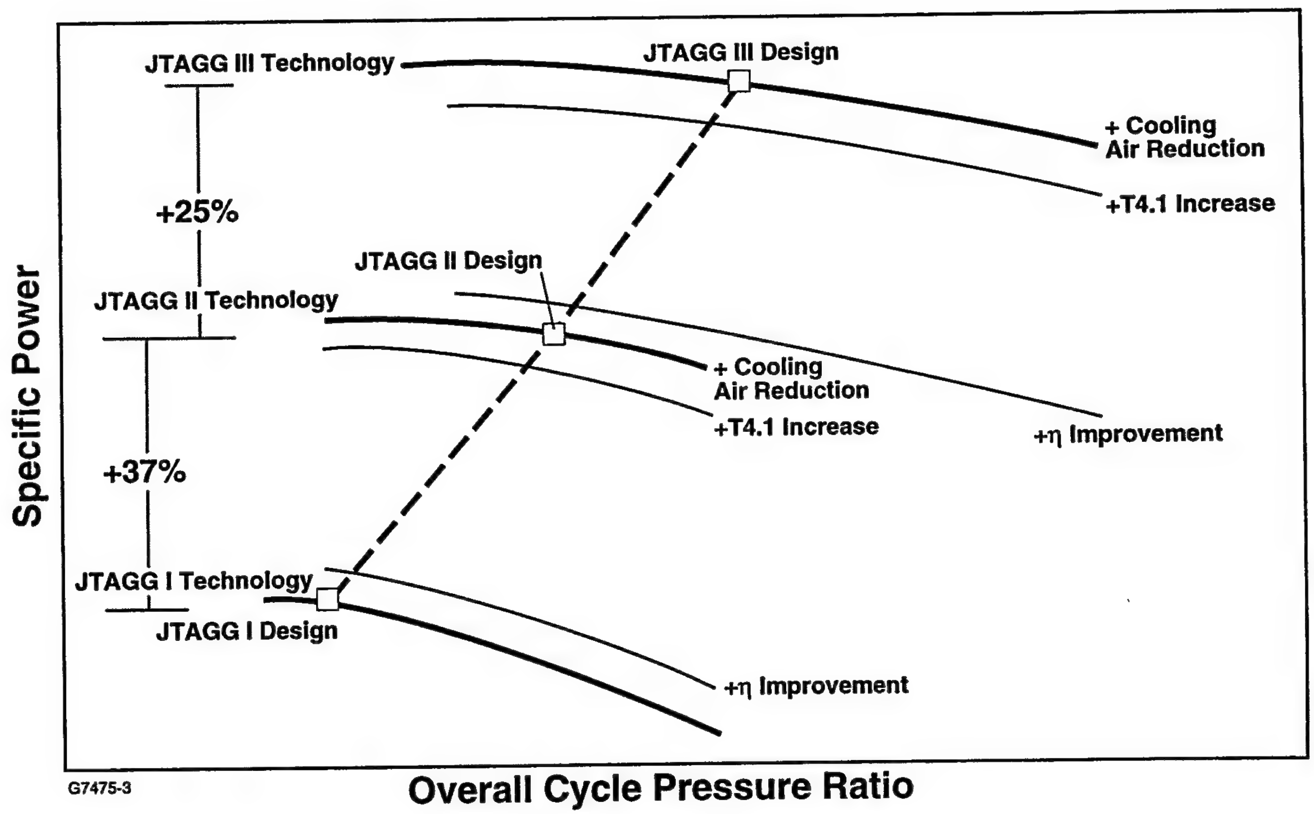
Cycle Temperature Technology for Power Density



$T_{4.1}$ drives specific power and core specific thrust

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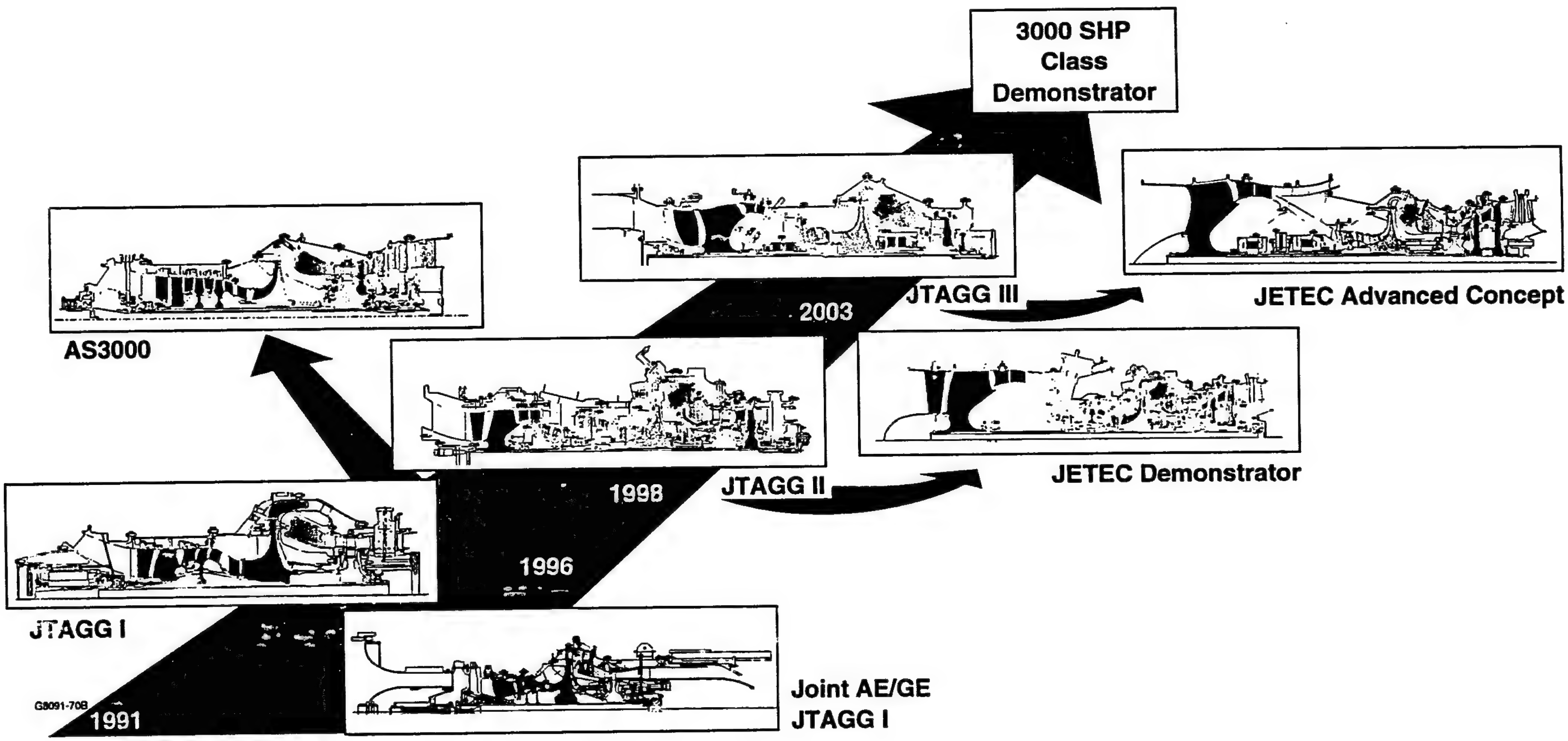
Engine Building Block Roadmap



Note: Cross Sections Are Not to Scale

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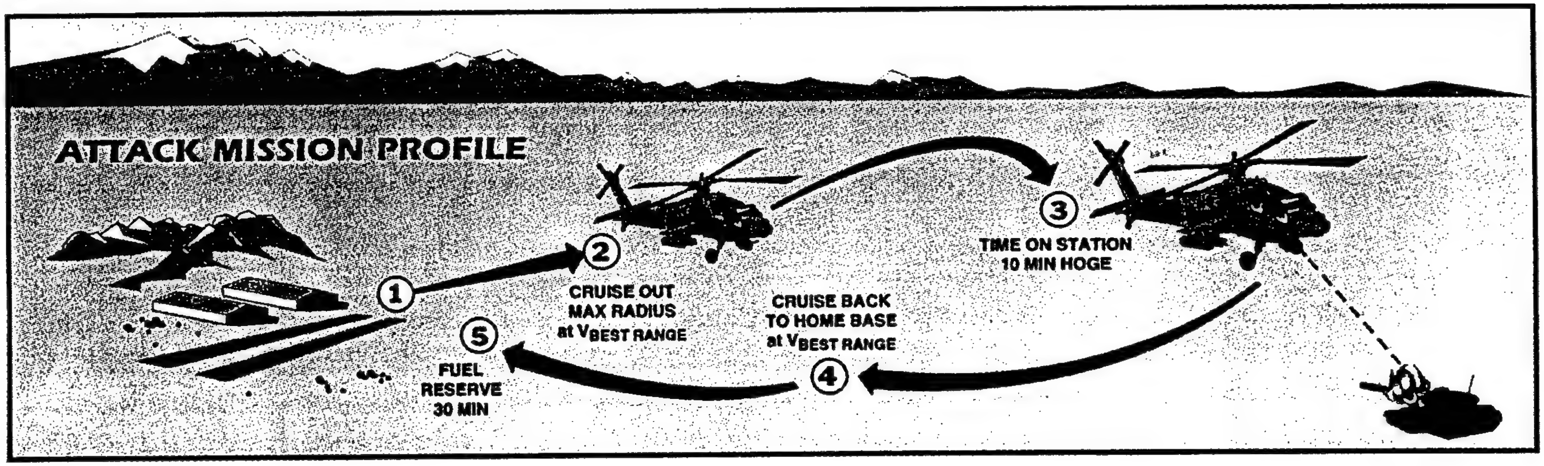
AS3000 Engines Provide Significant Increase In AH-64 Mission Capability



TOGW: ~17,000 lb

Current Payload: 2,278 lb

- 8 Hellfire
- 38 Rockets
- 598 30mm rounds

- Fuel Load: 2,440 lb

Engines	Current	AS3000 -30% SFC +80% shp/wt
Mission Radius	215	340 +58%
Payload	Current	+502 rounds +17%

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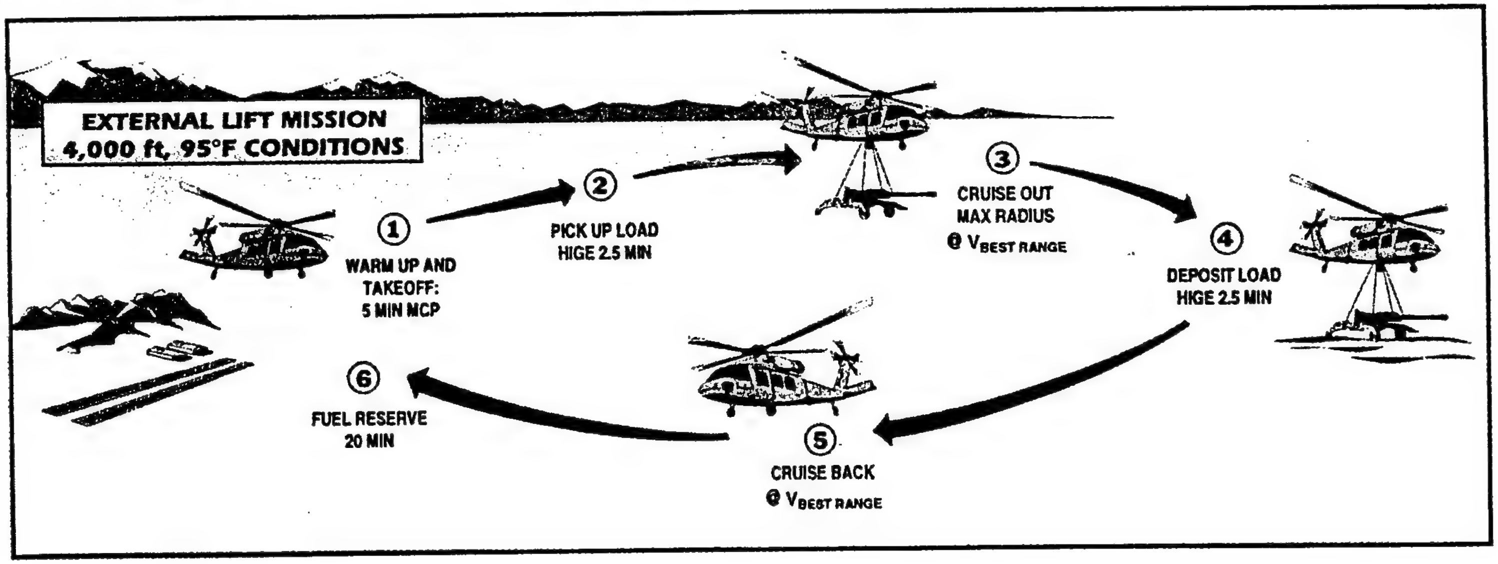
AS3000 Engines Provide Superior Mission Capability for UH-60 (X)



Assumptions
- **Fuel load: 2339 lb**
- **Wide chord blade**

* *Engine sized for 25,000 lb HOGE capability at 4k, 95 IRP (~2680 hp SLS)*

Current UH60-L 4k, 95 capability
- **19,500 lb HOGE at IRP**
- **Payload ~4700 lb external with mission radius of 225 km**

Engines	Growth HP Current SFC	AS3000 -30% SFC +60% shp/wt
Mission Radius, km	155	245
TOGWT, lb	25,000	25,000
Payload Capability, lb	8,900	9,100

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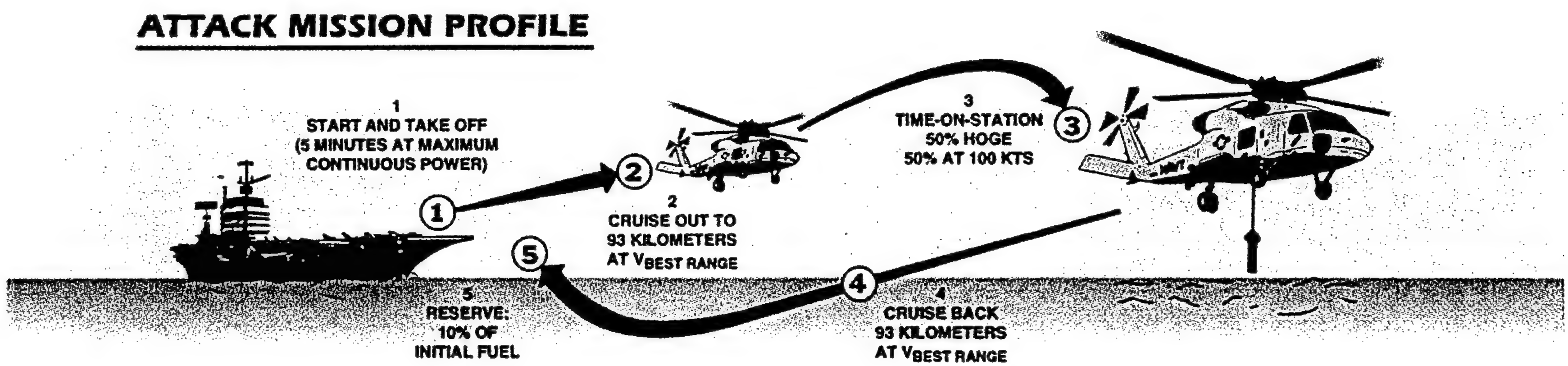
AS3000 Engines Provide 100% Increase in SH-60 Time-On-Station



Payload: 1,600 lb
- Two acoustic homing torpedos

Engines	Current	AS3000 -30% SFC
SHP	1,850	2,700
TOGW	21,740	25,000
Mission Radius	93 km	93 km
Time-On-Station	187 min	395 min +110%

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IHPTET Technologies in UCAV

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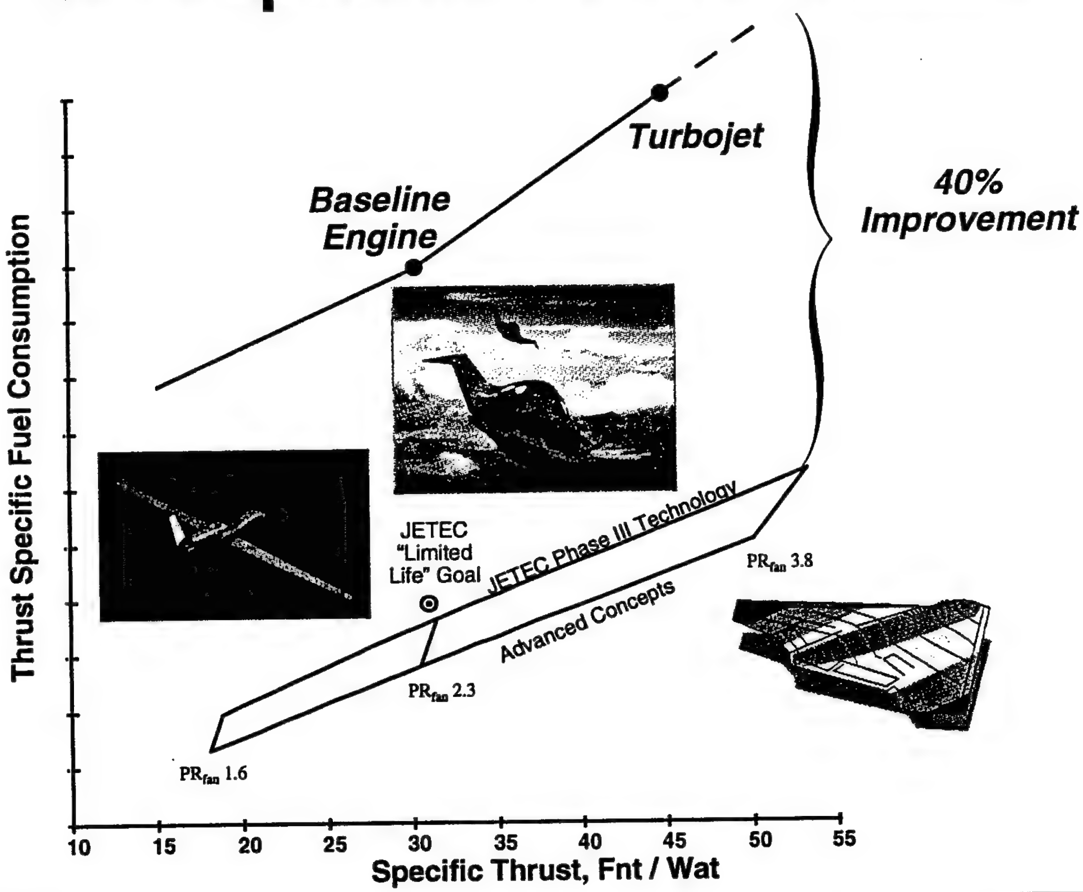
TSFC/Specific Thrust Tradeoff



- Thrust-Specific Fuel Consumption

$$TSFC \sim \frac{SFC}{\eta_{propulsion}}$$

$$\eta_{propulsion} = \frac{1}{\left(\frac{Fn}{Wa}\right)\frac{g_c}{2Vo} + 1}$$

SFC ~ Set by technology and Thermodynamic Cycle

Application determines specific thrust and propulsive efficiency. Technology sets thermal efficiency (SFC)

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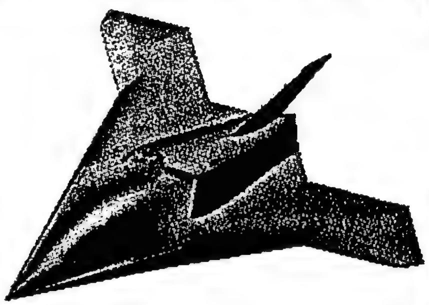
IHPTET Technology Infusion into F124 Provides Demonstrator Engine for Uninhabited Combat Aerial Vehicles (UCAV)

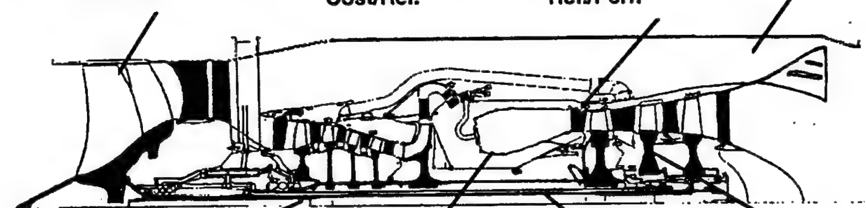
Applications



Air to Air

Air to Ground

Technologies



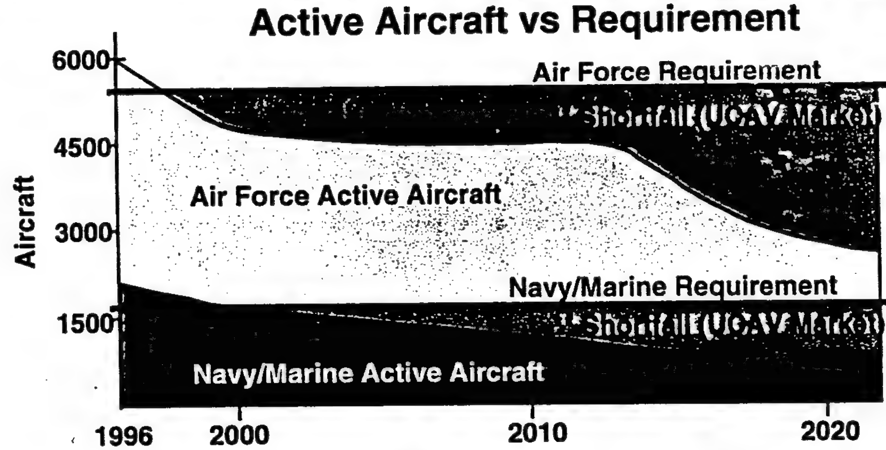
Benefits

Technical Benefits
- Small size ideal for new class of UCAV
- Engine can incorporate advanced technology derived from other AE programs

Commercial Benefits
- UCAV is a new market opportunity
- Derivative F124 engines ideal for feasibility and capability demonstration
- Participation in demonstrators positions AE Production applications (2005-2010)

Potential Market

Active Aircraft vs Requirement



** Based on Boeing Data

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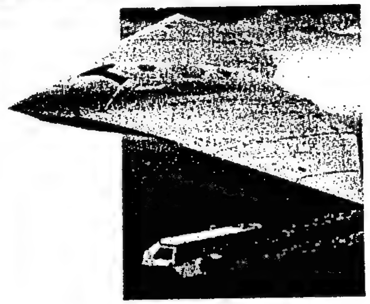
JETEC III Technology Yields Advanced Engine for Future UCAV

Applications

USAF Air-to-Ground



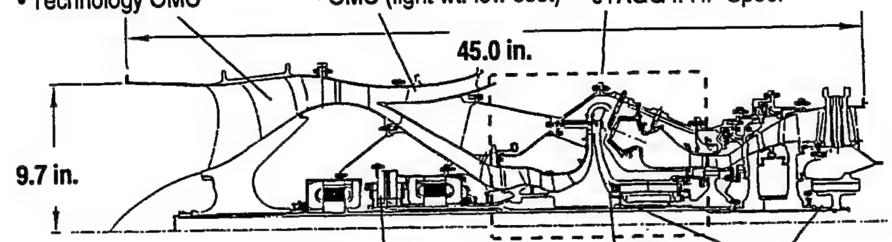
USN Air-to-Air

Benefits

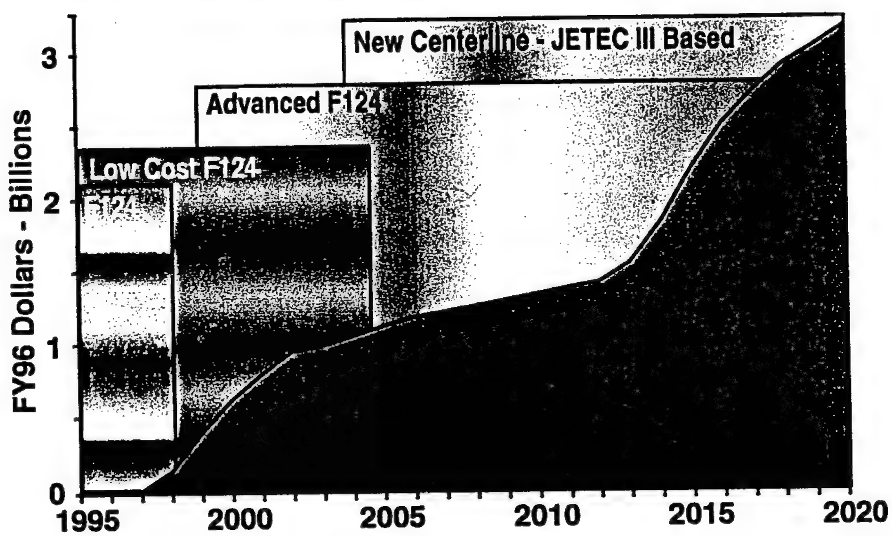
Technical Benefits
- Superior SFC (-30%)
- High specific thrust - Fn/wt>10 (Dry)
- Low cost - $/lbf <50% of F124

Commercial Benefits
- UCAV Major new market opportunities (2005+)
- Near term opportunity for F124/F125 in US military (1999+)

Technologies



UCAV Engine Market Potential



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Challenges of Advanced Technologies

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Propulsion Challenges
Cost: A Major Issue

Controls and Accessories Cost Reduction

- Combine engine control functions with aircraft control

Manufacturing Processes

- Extensive use of castings
  - Spray casting
  - Permanent mold casting
- Ceramics
  - Blisks

Technology

- OMC
- Oilless bearings
- Integral electrical components
  - Starting and power extraction

Aircraft Bleed Air and Electrical Power

- Propulsion system or APU?

Performance and Life Impact on Cost

- TSFC reduction drives propulsion system cost - must be assessed with respect to mission benefit and overall aircraft cost

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IHPTET Technologies in T800

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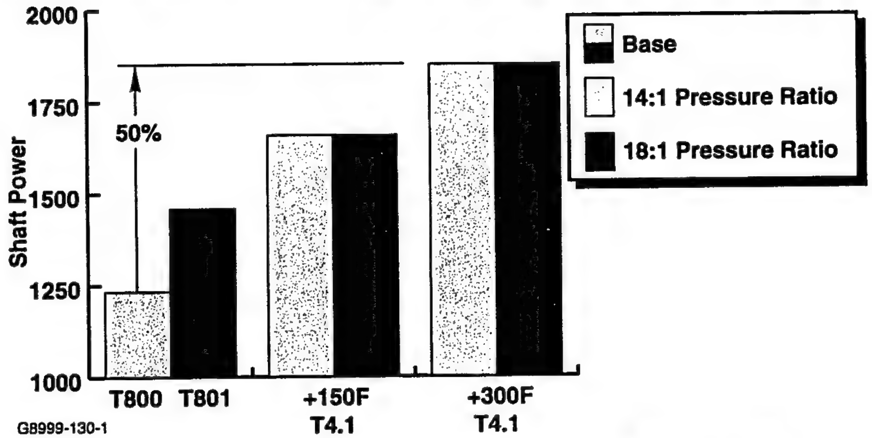
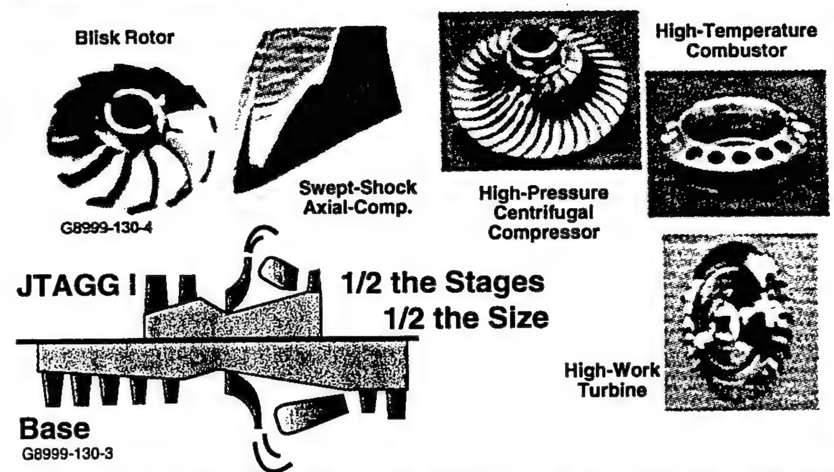
JTAGG Provides Technology for T800 Growth

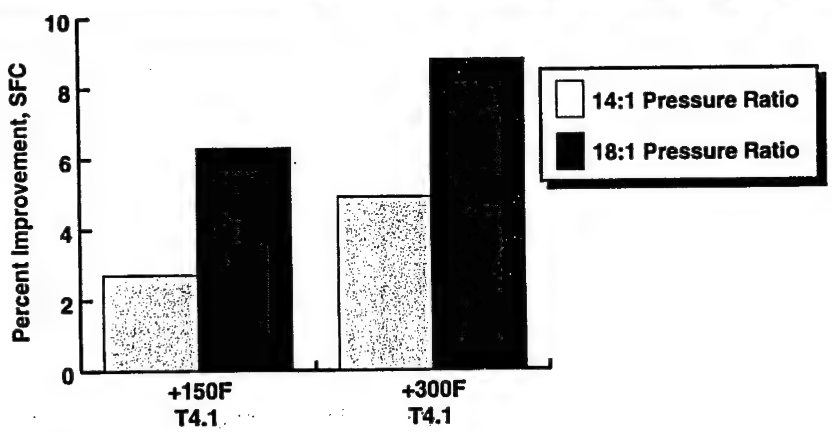
Growth T800 Power



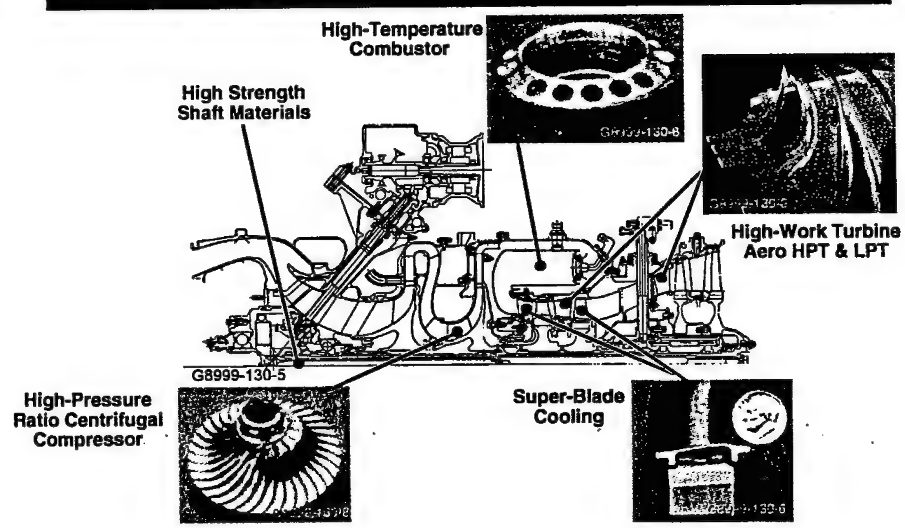
Key Technologies Demonstrated - JTAGG I



Growth T800 SFC



T800 Growth Based on JTAGG Technology



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AS3000 Turboshaft Engine for T700 Replacement in

- Apache
- Blackhawk
- Seahawk

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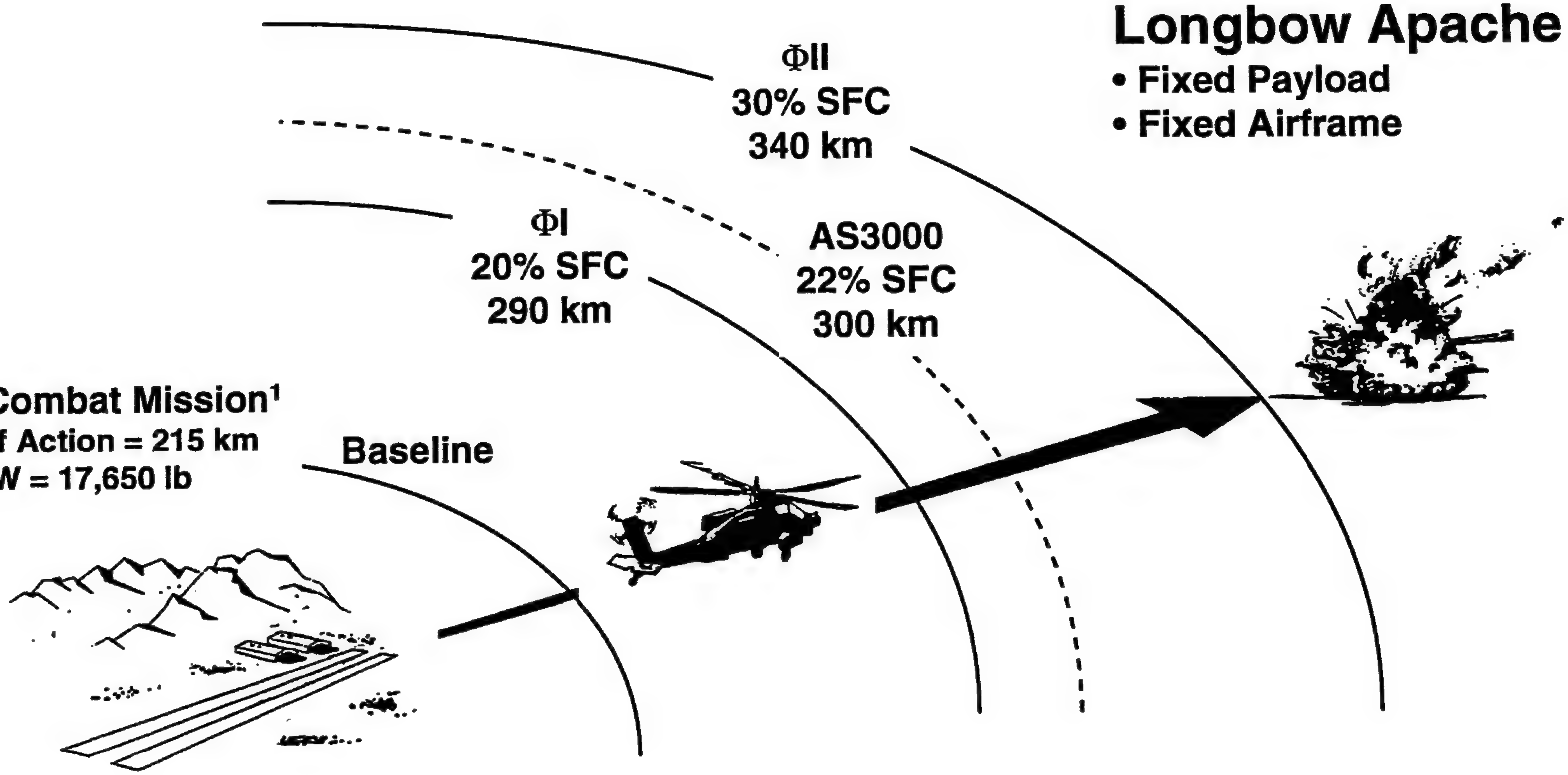
Warfighter Priorities For AAN

Army Requirements: Increased Payload and Range



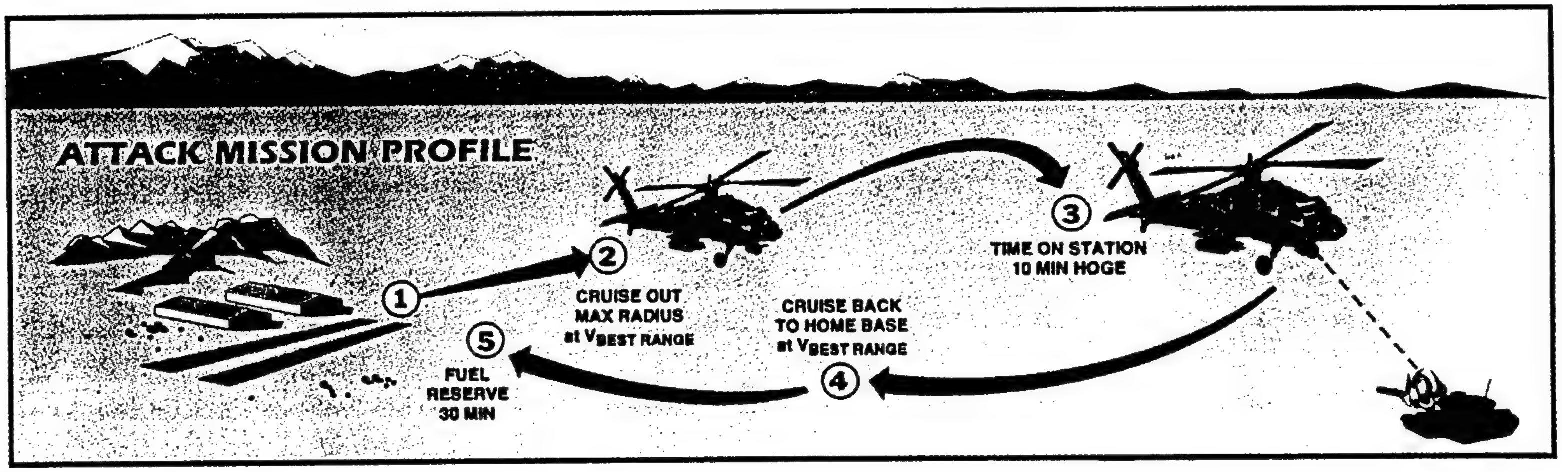
[1]Mission provided by S. Hoff

AS3000 designed to provide Longbow Apache with 300 km Radius of Action

V8397-59

WARFIGHTER PRIORITIES FOR AAN

IHPTET TECHNOLOGY ENGINES PROVIDE SIGNIFICANT INCREASE IN AH-64 MISSION CAPABILITY



TOGW: ~17,000 lb

Current Payload: 2,278 lb

- 8 Hellfire
- 38 Rockets
- 598 30mm rounds

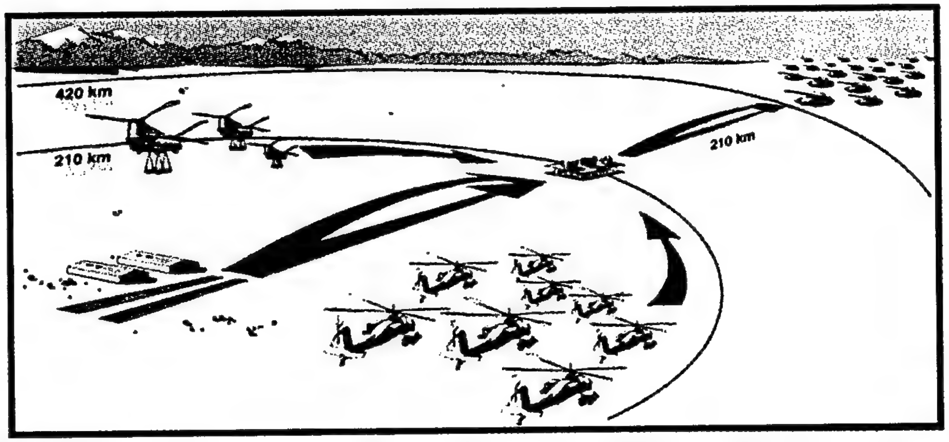
Fuel Load: 2,440 lb

Engines	Current	Phase I -20% SFC +40% shp/wt	Phase II -30% SFC +80% shp/wt	Phase III -40% SFC +120% shp/wt
Mission Radius	215	285 km (+32.5%)	340 km (+58%)	420 km (+95%)
Payload	Current	+320 Rounds (+11%)	+502 Rounds (+17%)	+602 Rounds (+20%)

V8397-18

Integrated High Performance Turbine Engine Technology

Provides Mission Flexibility for AAN



MSN: AH64 Company to Engage Tank Unit at 420 km and Return to Base

IHPTET DRIVERS

- HIGH PRESSURE RATIO
- HIGH CYCLE TEMP
- HIGH TEMPERATURE, HIGH STRENGTH/WT MATERIALS
- AFFORDABLE DESIGNS

IHPTET PHASE III GOALS

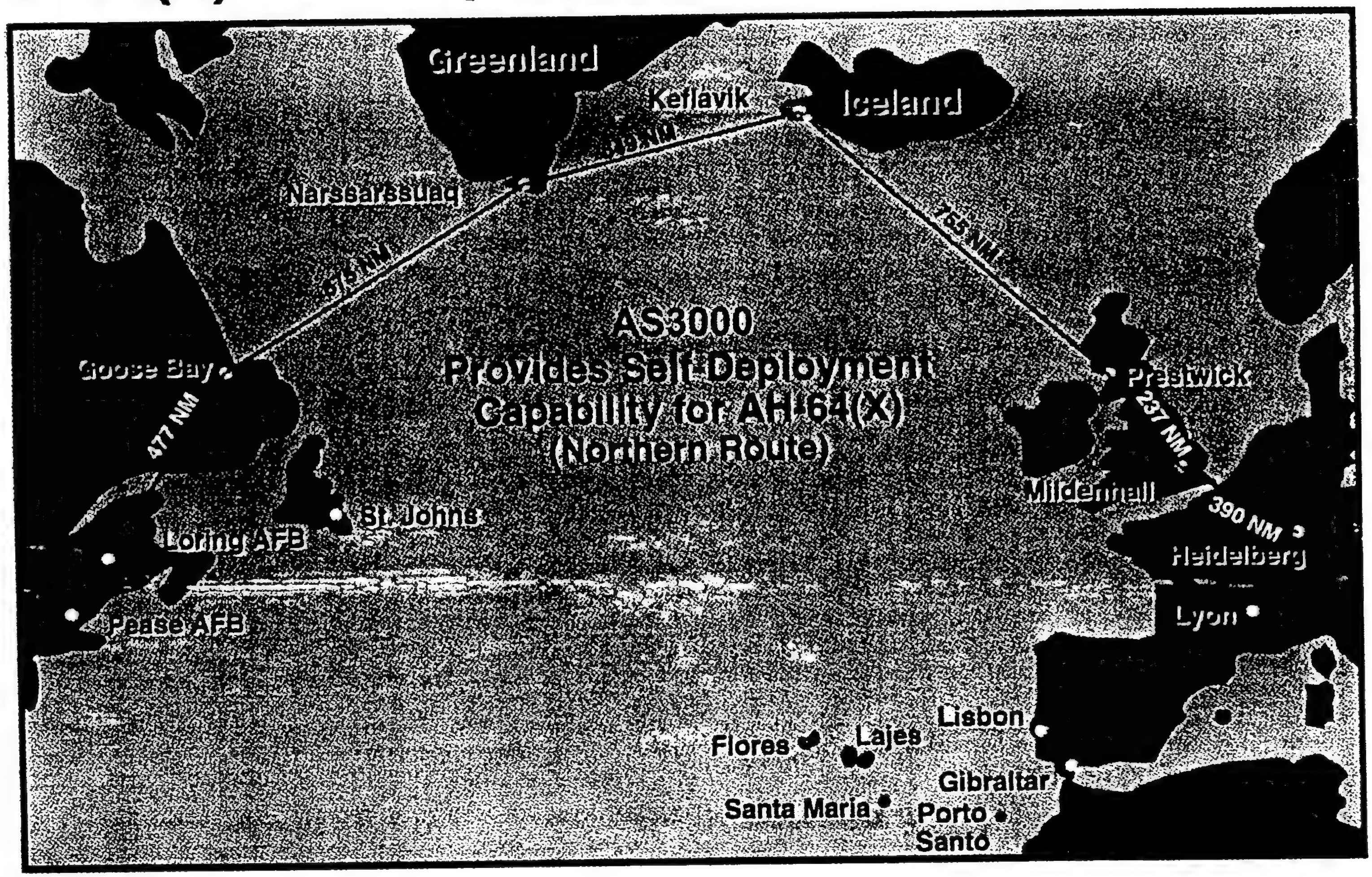
- 40% SFC REDUCTION
- 120% POWER TO WEIGHT INCR
- 35% REDUCTION IN PRODUCTION & MAINTENANCE COST

	TODAY	WITH IHPTET III ENGINES
Attack Aircraft		
FARRP Support Aircraft		NONE REQUIRED
Mission Fuel	6800 gal.	3000 gal.
Crew Members	28	16

V8397-18

WARFIGHTER PRIORITIES FOR AAN

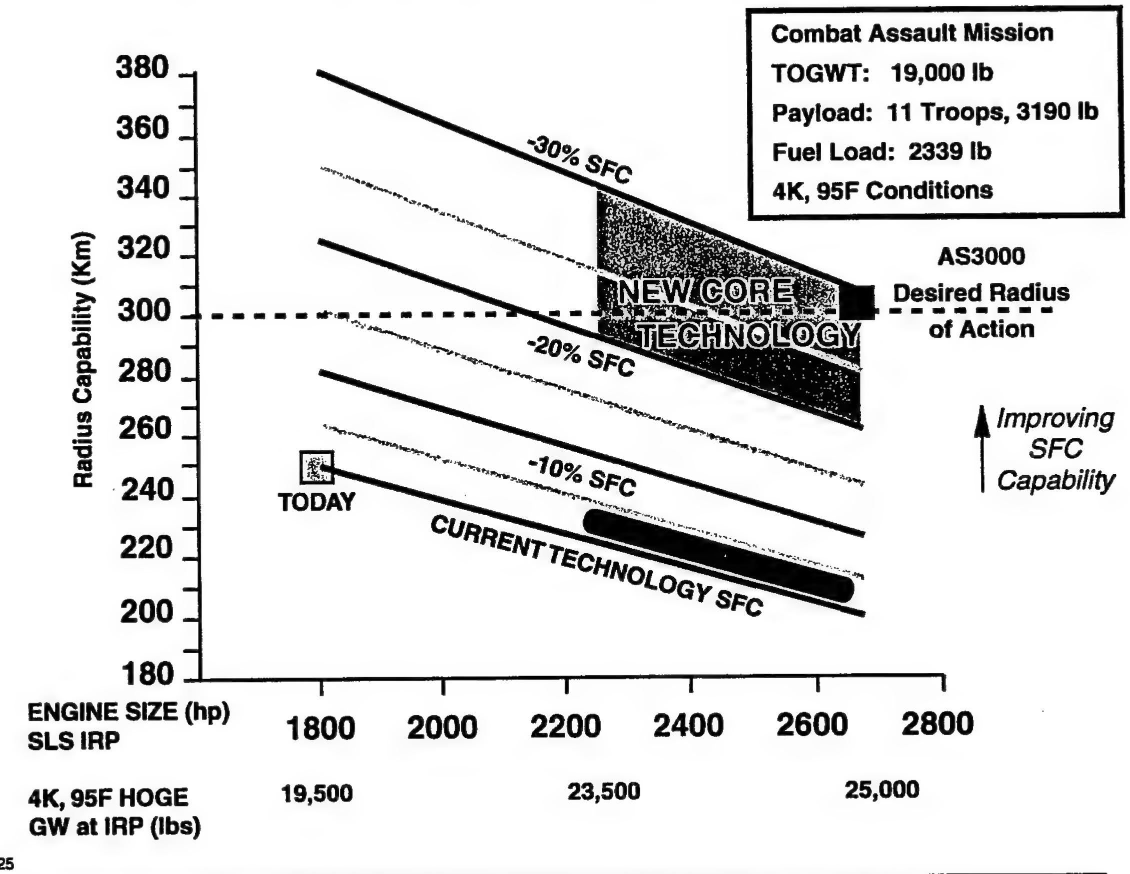
AH-64(X) Self-Deployment Capability



V8397-19

WARFIGHTER PRIORITIES FOR AAN

UH60(X) Performance Comparison
New Core versus Growth Engine



AS3000 required to meet AAN mission

V8397-25

RESONANCE STRESS, FLUTTER & STABILITY CHALLENGES IN AIRCRAFT GAS TURBINE ENGINES

Om Sharma, Gary Hilbert, Yehia El-Aini

Pratt & Whitney

400 Main Street, E. Hartford, CT 06108

Alan Epstein

Massachusetts Institute of Technology

77 Massachusetts Ave., Cambridge, MA 02139

Presented at the Georgia Tech Workshop on
Needs & Technologies for Future Gas Turbines June 15-16, 1998

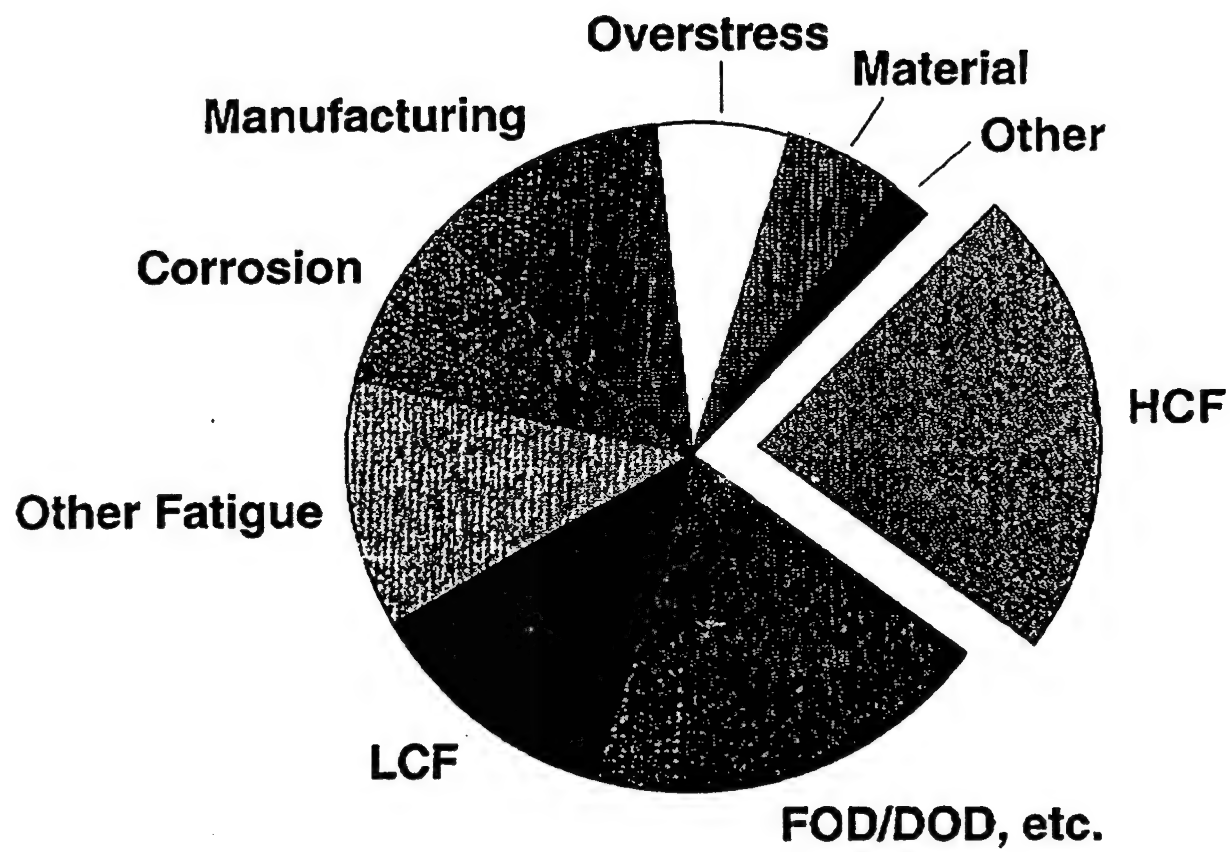
OUTLINE

- BACKGROUND
- APPROACH
- PROGRESS
- SUMMARY & FUTURE DIRECTION

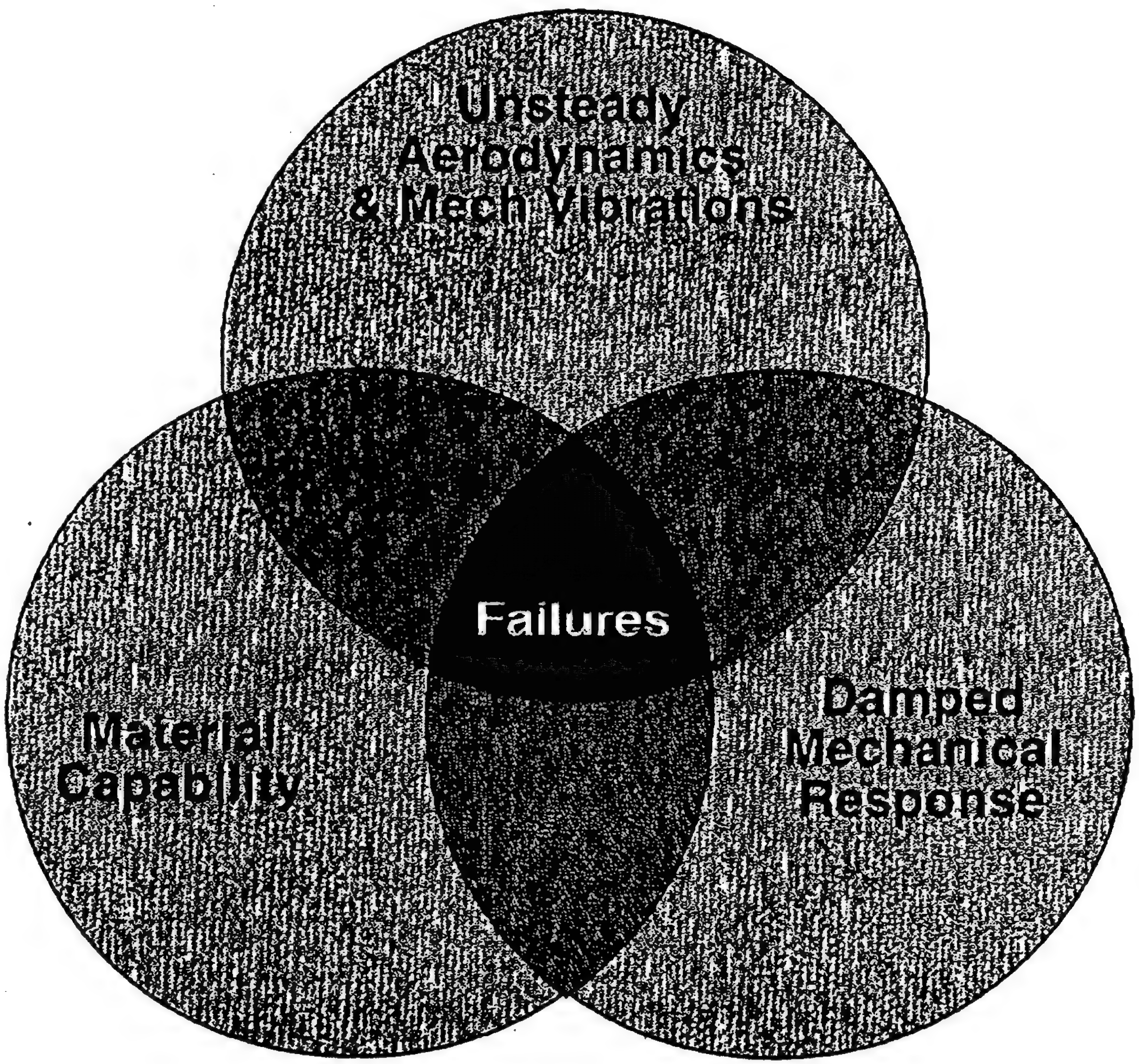
AEROENGINE TURBOMACHINERY ISSUES

- Aero performance
  - Pressure rise, efficiency, flow capacity
- Performance limiting instabilities
  - Rotating stall and surge
  - Inlet buzz
- Life limiting instabilities
  - Flutter and forced structural response
- You can fly engines with poor efficiency, you cannot fly engines which are unsafe, *i.e.* subject to
  - Surge
  - Flutter

JET ENGINE FAILURE MODES



HIGH CYCLE FATIGUE
- Primary Technical Factors -



FLUTTER AND FORCED RESPONSE

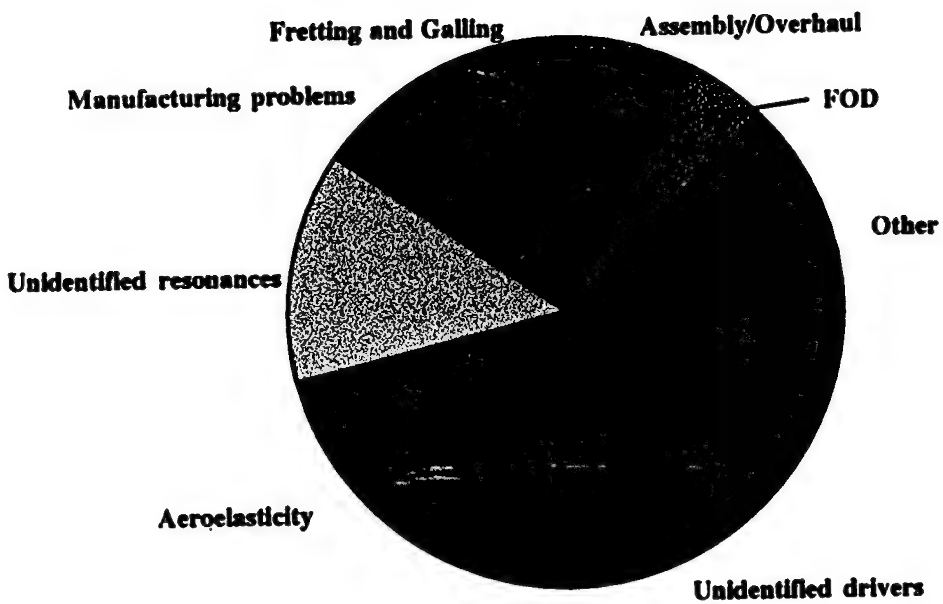
- Introduction
  - Many kinds of aeromechanical problems in turbomachinery
  - Flutter, self-excited aeromechanical vibration
  - Forced response
  - These coupled aero-structures problems cannot now be accurately predicted
- Why do we care about aeromechanics?
  - All new engines have problems in development
  - Many engines develop problems in the field
- Technical questions
  - What is aero and structural damping at each operating point?
  - Do flow and structural dynamic codes give accurate answers?
  - How to generate data for exploration and code validation?
  - How to develop first principles, accurate prediction technology?

Background

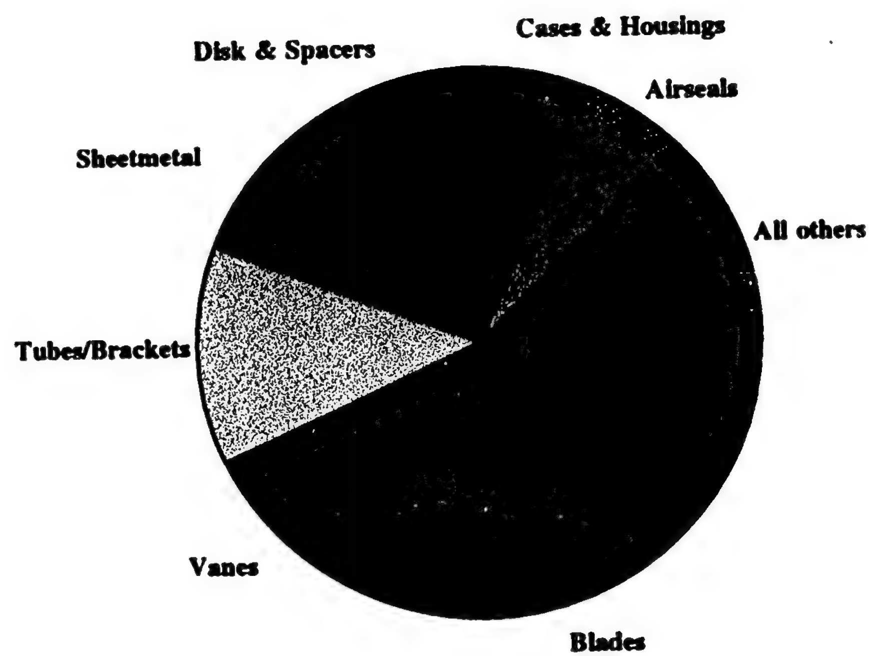
HCF: **" Metal fatigue that results in cracking or fracture from a large number of stress cycles well below the yield strength of the material"**

- *Engine components must meet or exceed life requirements*
- *HCF is a major readiness issue for the Air Force*
- *HCF problems may account for ~25% of development problems*
- *Average development program has 2 serious HCF problems*
- *Approx. 20% of HCF problems involve Titanium blades*
- *HCF is not a safety issue for commercial, but can result in class A loss in military (single engine) applications.*

Background (cont.)

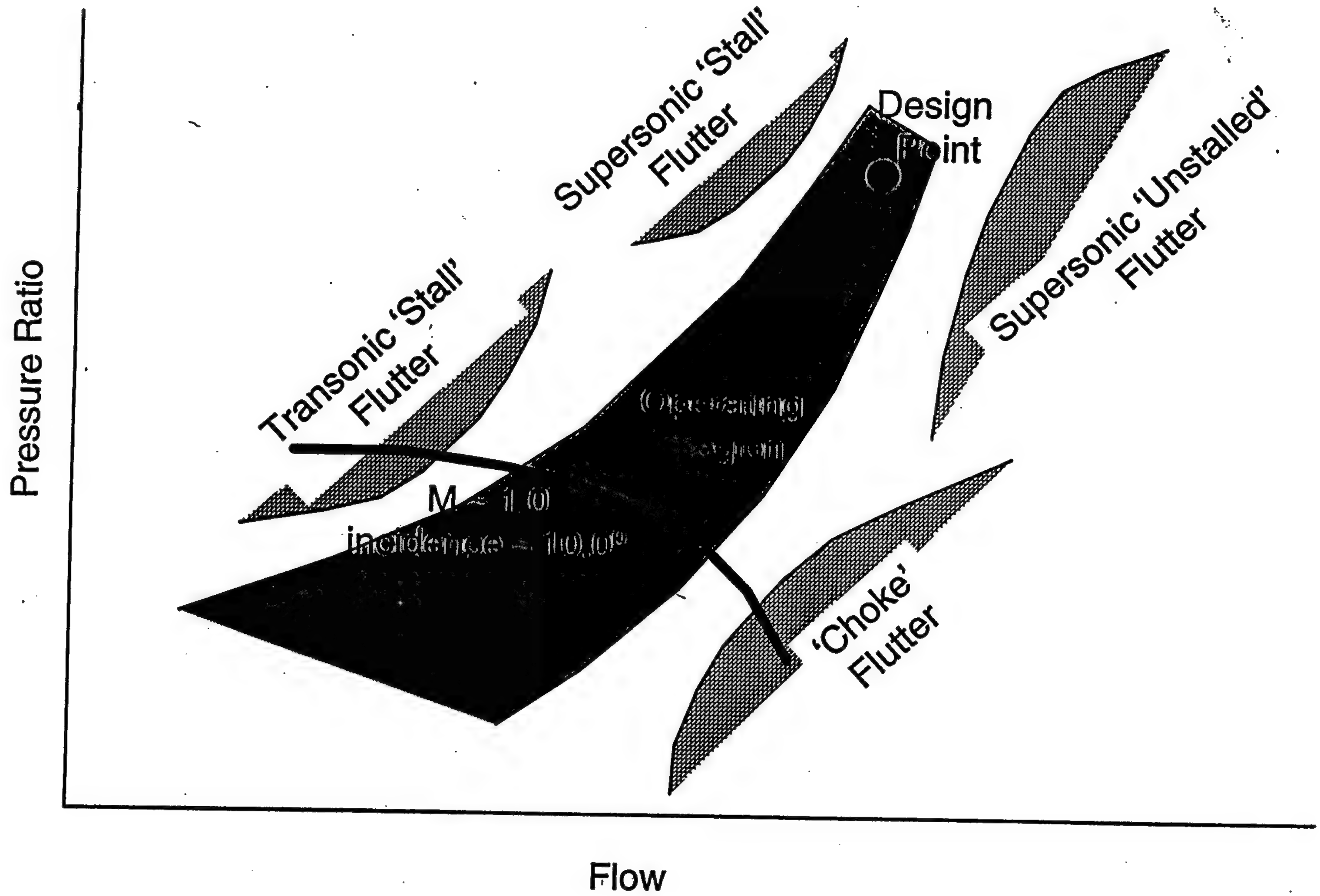


Major causes of HCF problems

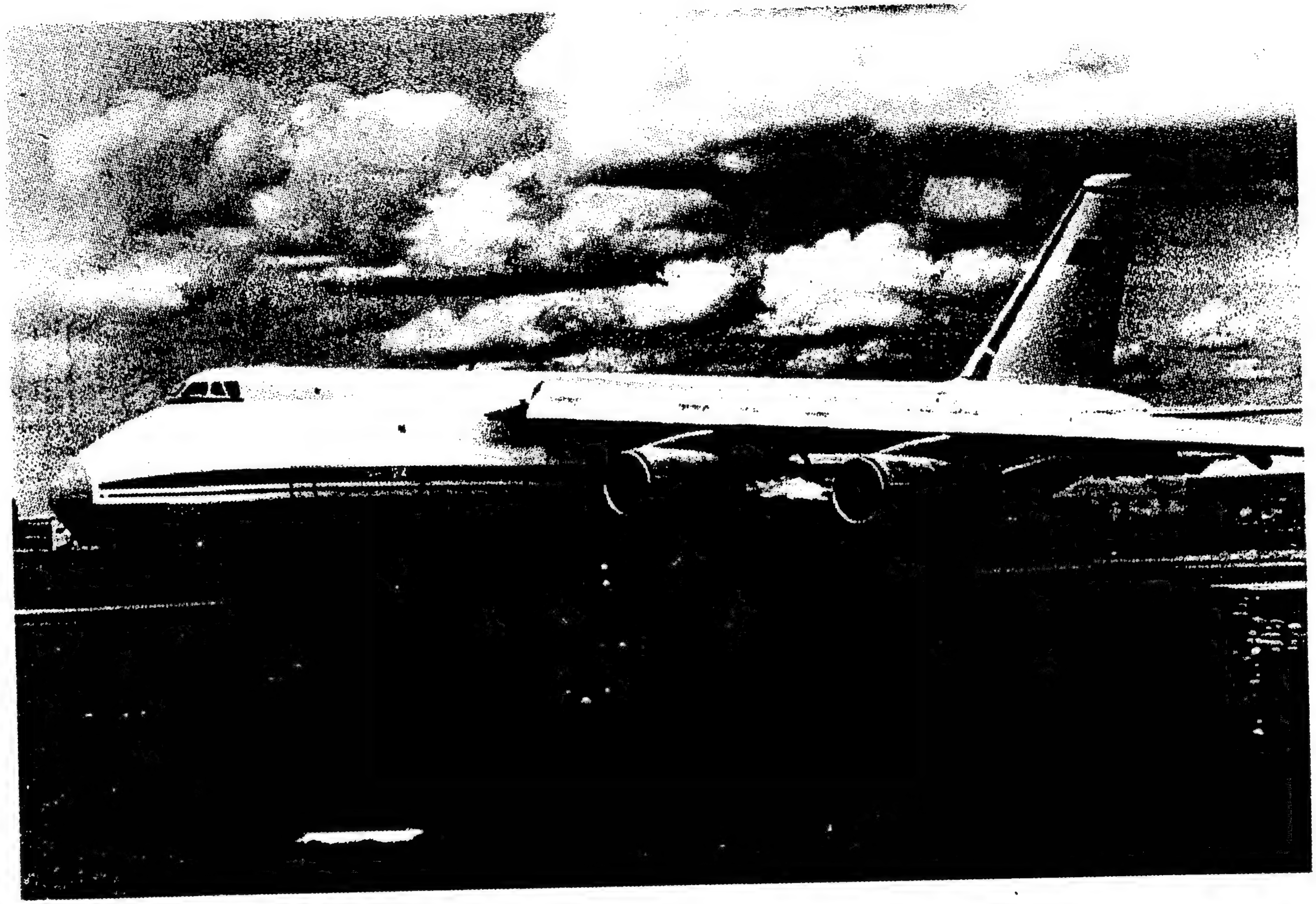


HCF Problems as a function of component

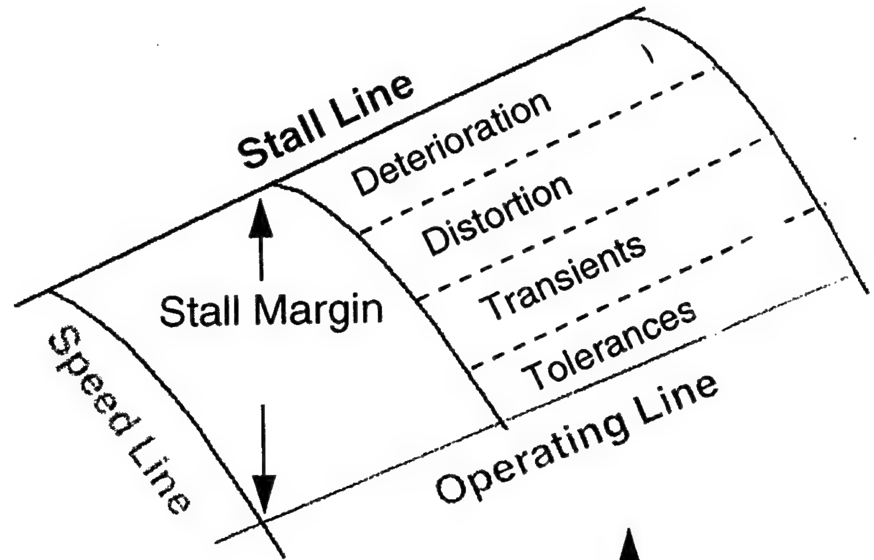
Transonic 'Stall' Flutter is the Main Flutter Threat for Low Aspect Ratio Shroudless Fans



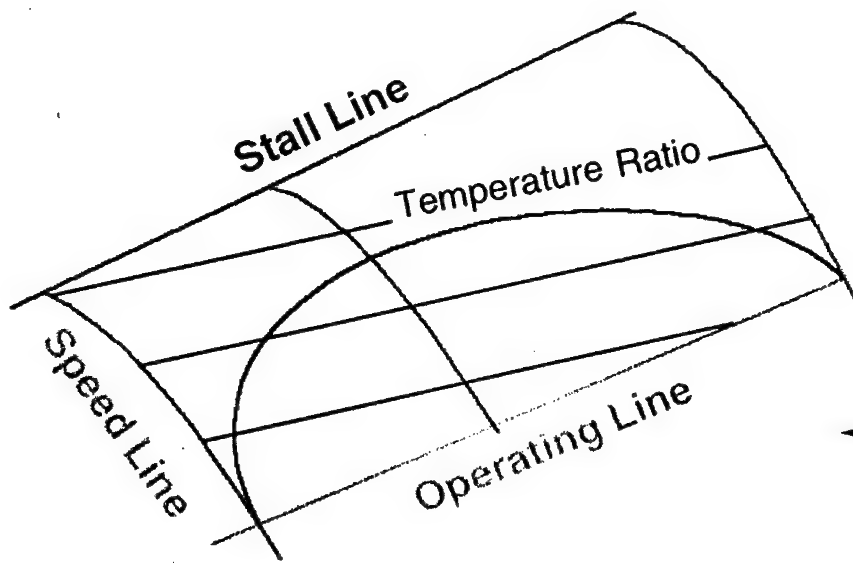
Engine Surge



Stall Margin



Stall Margin



Acceleration Transient

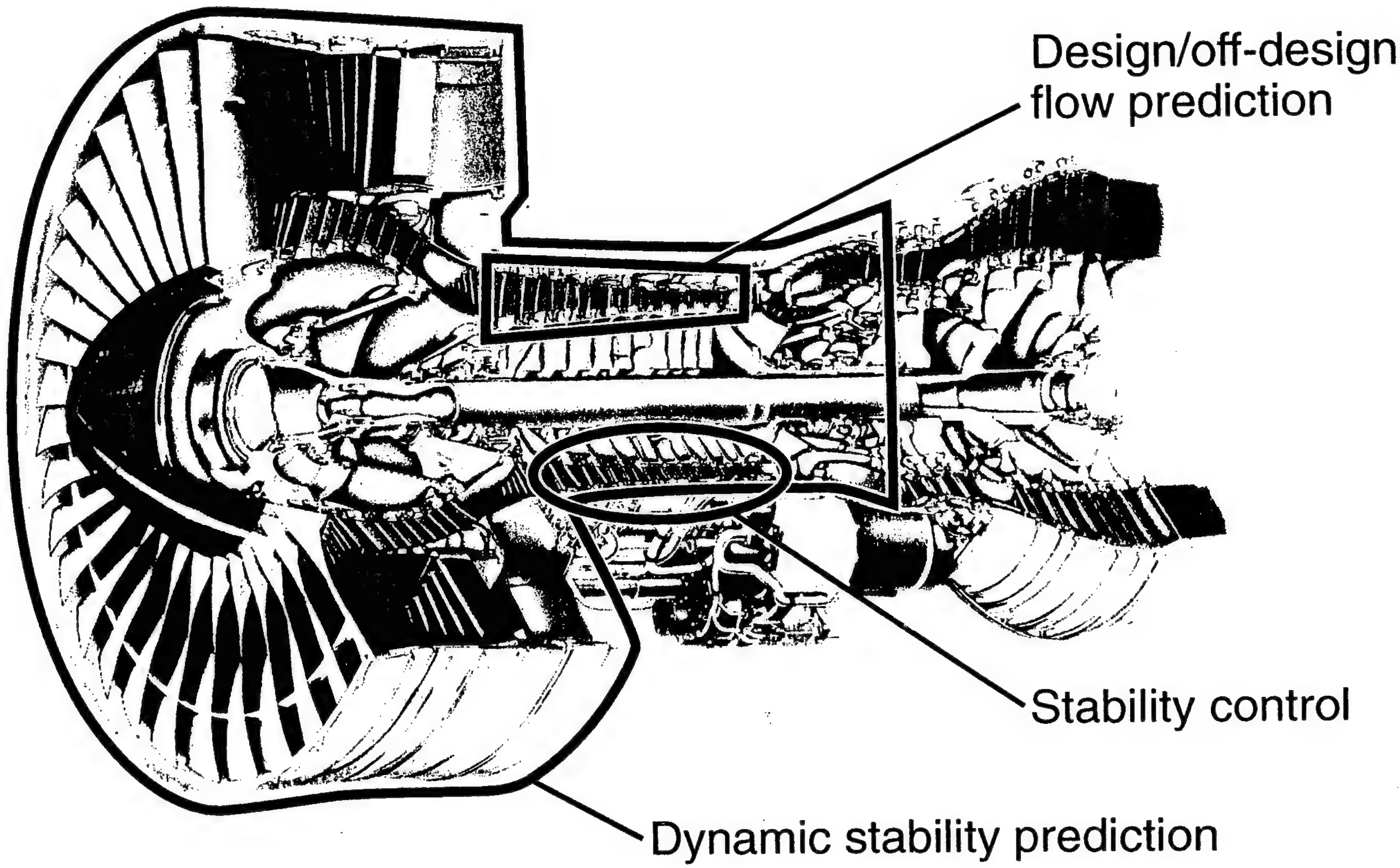
APPROACH

- DEVELOP PREDICTION SYSTEMS BASED ON "PHYSICS BASED MODELS"

- DEVELOP EXPERIMENTAL TECHNIQUES TO ALLOW APPROPRIATE DATA ACQUISITION IN A REALISTIC ENVIRONMENT

APPROACH

DEVELOP PHYSICS BASED PREDICTION SYSTEMS



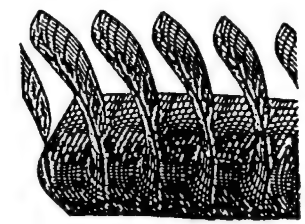
- Develop Instrumentation & Data Analyses Systems

CODE DESCRIPTION (NASTAR CODE)

"NASTAR" - NAvier-STokes analysis of Arbitrary Regimes

Steady Navier-Stokes Solver
Implicit Pressure Correction Algorithm
K-E Two-Layer Turbulence Model
Models to account for Multistages

Governing Equations



Continuity Eq. $(\partial/\partial x_i)\rho u_i = 0$

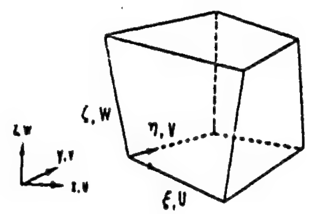
Reynolds Averaged Navier-Stokes Eq. $(\partial/\partial x_i)\rho u_i u_j = -\partial P/\partial x_j + (\partial/\partial x_i)[(\mu + \mu_t)(\partial u_i/\partial x_j + \partial u_j/\partial x_i)] - (2/3)\rho k \delta_{ij}$

Turbulent Viscosity $\mu_t = C_\mu \rho k^2/\epsilon$

K-Eq. $(\partial/\partial x_i)\rho u_i k = (\partial/\partial x_i)[(\mu_t/\sigma_t)(\partial k/\partial x_i)] + P - \rho\epsilon$

Epsilon-Eq. $(\partial/\partial x_i)\rho u_i \epsilon = (\partial/\partial x_i)[(\mu_t/\sigma_\epsilon)(\partial \epsilon/\partial x_i)] + (\epsilon/k)(C_1 P - C_2 \rho\epsilon)$

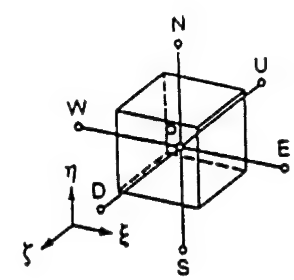
Transformation of the Equations



General Conservation Eq.

$$1/J\{[\rho G_1\phi]_\xi + [\rho G_2\phi]_\eta + [\rho G_3\phi]_\zeta\}$$
$$= 1/J\{[J\Gamma\alpha_1\phi_\xi]_\xi + [J\Gamma\alpha_2\phi_\eta]_\eta + [J\Gamma\alpha_3\phi_\zeta]_\zeta + S\} + S^\circ$$

Implicit Finite Volume Approach



Algebraic Eq. $A_P\phi_P = A_E\phi_E + A_W\phi_W + A_N\phi_N + A_S\phi_S + A_D\phi_D + A_U\phi_U + (S + S^\circ)J\Delta\xi\Delta\eta\Delta\zeta$

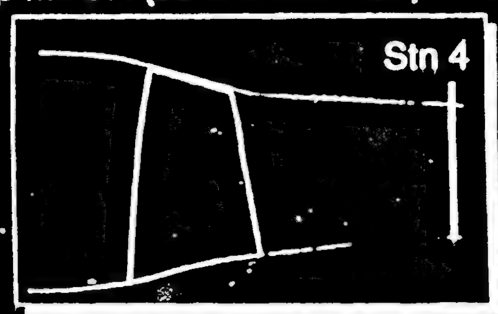
Pressure Correction Equation

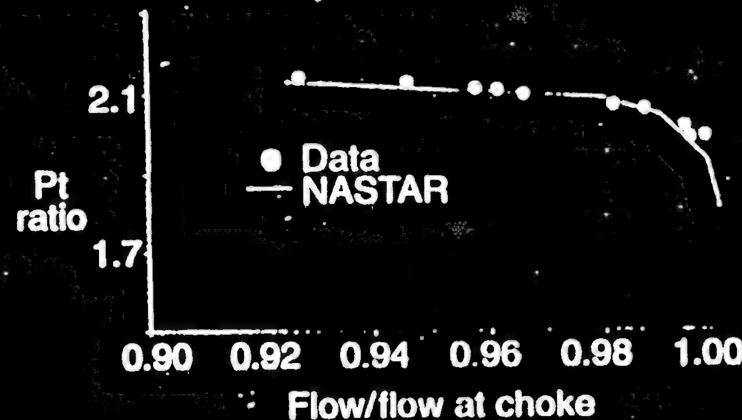
$$\frac{\partial(\frac{U}{RT}P')}{\partial\xi} + \frac{\partial(\frac{V}{RT}P')}{\partial\eta} + \frac{\partial(\frac{W}{RT}P')}{\partial\zeta} = \frac{\partial}{\partial\xi}\left(B\frac{\partial P'}{\partial\xi}\right) + \frac{\partial}{\partial\eta}\left(C\frac{\partial P'}{\partial\eta}\right) + \frac{\partial}{\partial\zeta}\left(D\frac{\partial P'}{\partial\zeta}\right) - \dot{m}$$

CODE VALIDATION — STEADY

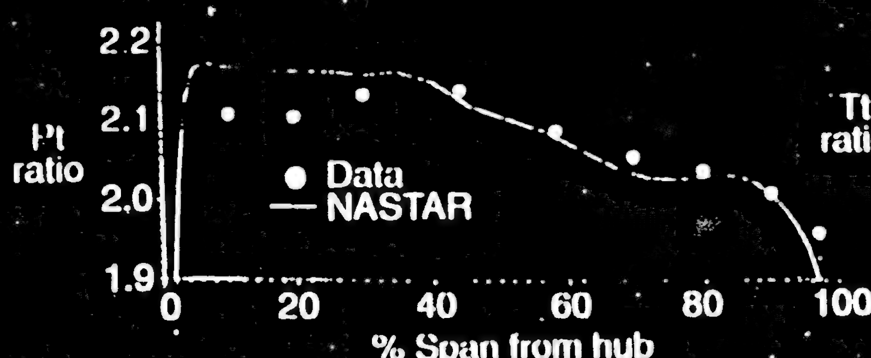
FANS: NASA ROTOR 37 — Rhie et. al. (1995)

Tip MACH (98% choke flow) = 1.41

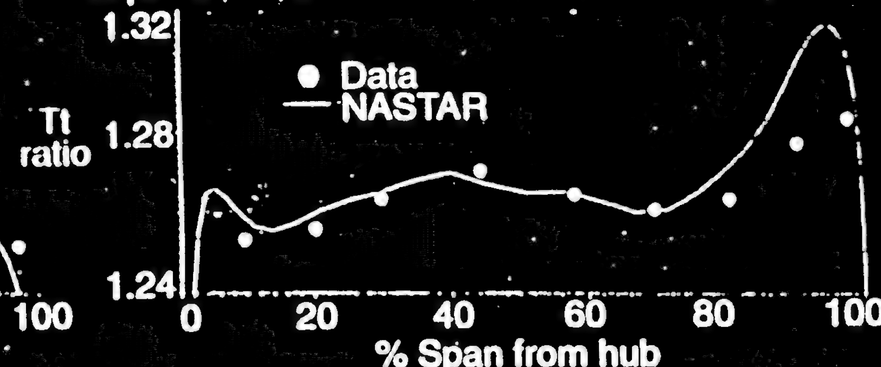




Total pressure ratio as function of flow at design speed



Spanwise pt ratio profile at peak efficiency condition



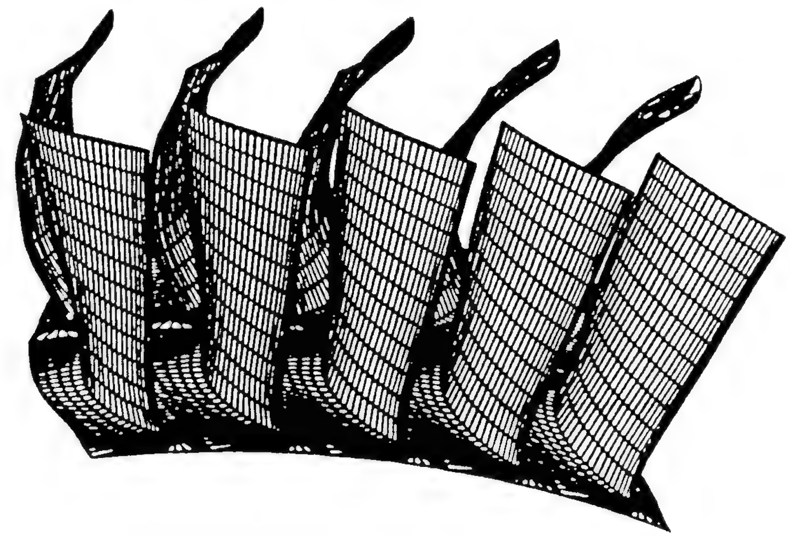
Spanwise Tt ratio profile at peak efficiency condition

Experimental data Ref Suder, K.L., et.al., "Experimental and computational investigation of the tip clearance flow in a transonic axial compressor rotor", 1994 ASME paper

96A0606-009

CODE DESCRIPTION (NiSTAR CODE)

Time-Accurate Navier-Stokes Solver
Explicit Ni Scheme
Baldwin-Lomax Turbulence Model
Unsteady Vane/Blade Interaction



- NAVIER-STOKES EQS IN INTEGRAL FORM

$$\frac{\partial}{\partial t}\int_V U dV = \int_V S dV - \oint_A [F dA_X + G dA_\theta + H dA_R]$$

- FINITE VOLUME APPROXIMATION

$$\Delta U_c = S_c \Delta t + [W_I - W_{I+1} + W_J - W_{J+1} + W_K - W_{K+1}]\frac{\Delta t}{V}$$

$$W_I \cong [F A_X + G A_\theta + H A_R]_I$$

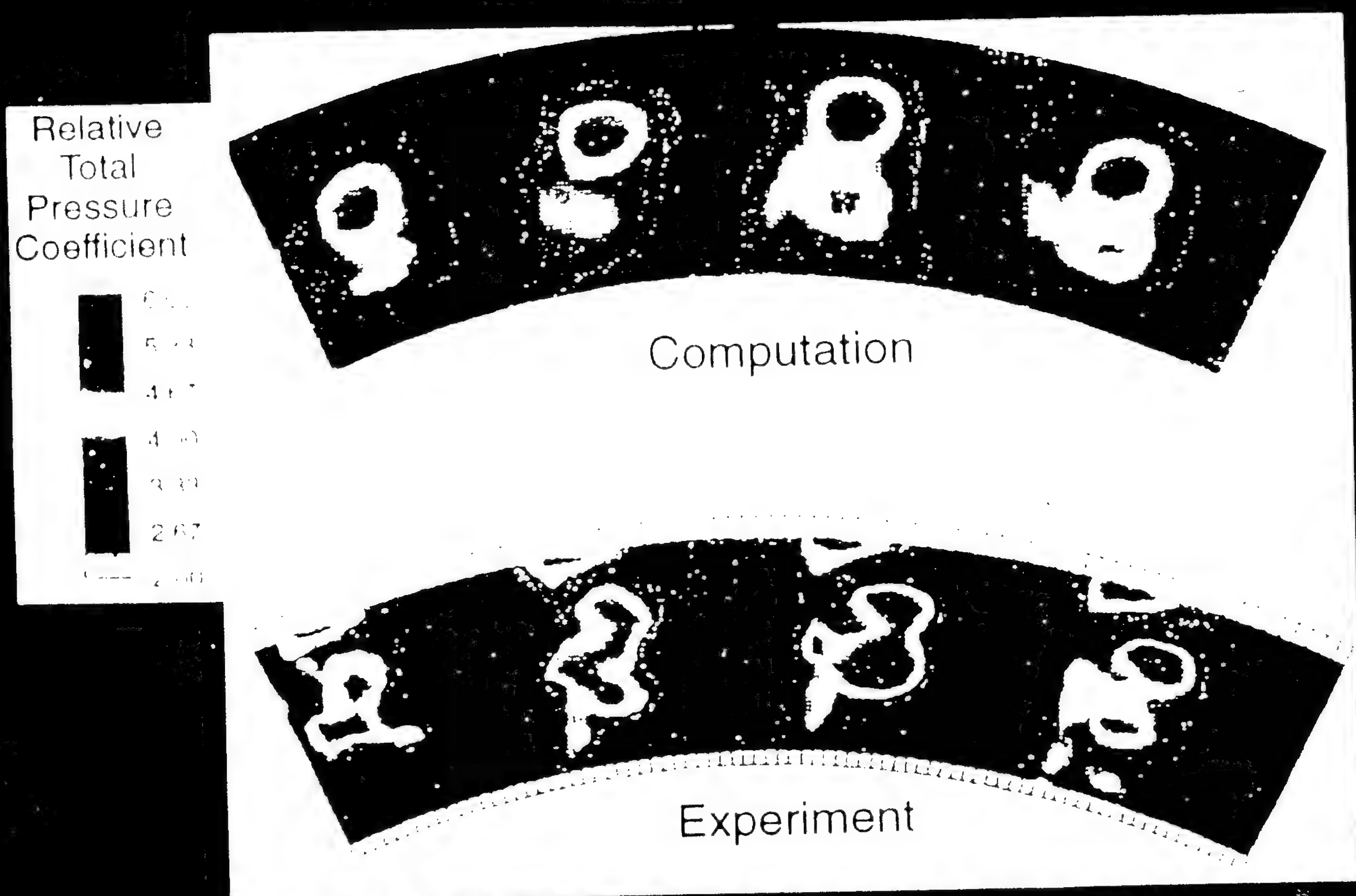
- DISTRIBUTION FORMULAE TO PROVIDE SECOND ORDER ACCURACY

$$(\delta U_1)_c = \frac{1}{8}[\Delta U - \Delta W_I - \Delta W_J - \Delta W_K]_c$$

- IMPLICIT RESIDUAL SMOOTHING TO OBTAIN FAST PERIODIC UNSTEADY RESULTS

CODE VALIDATION – UNSTEADY

PERIODIC ELIMINATION OF A TURBINE ROTOR ROOT SECONDARY FLOW VORTEX PREDICTED BY THE CODE



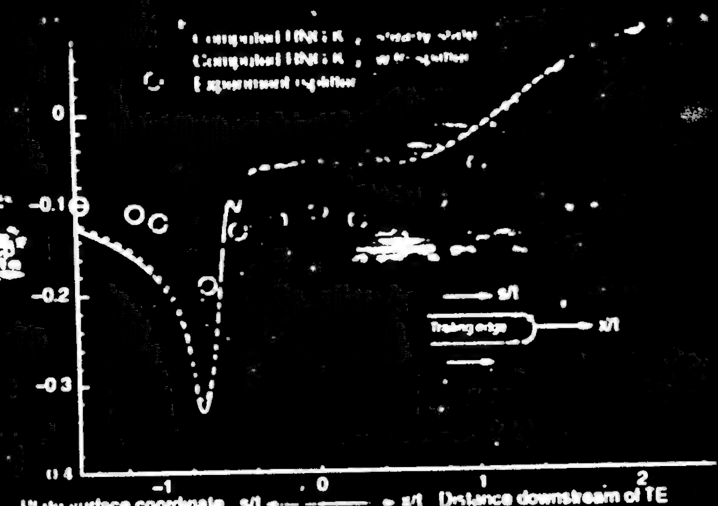
96A0606-026

TURBULENCE MODELS NEED TO ACCOUNT FOR UNSTEADINESS EFFECTS

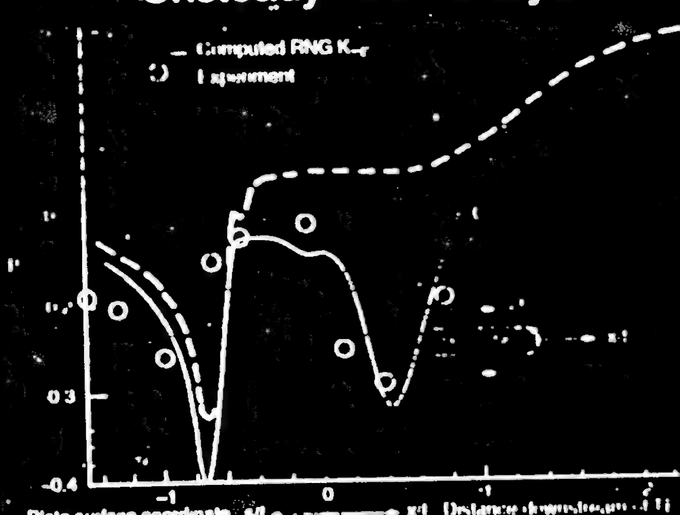
Unsteady multistage Navier-Stokes

- Unsteady viscous effects
  - Blade wake convection
  - Wake/boundary layer interaction
  - Blade trailing edge wake shedding

Steady RNG analysis



Unsteady RNG analysis

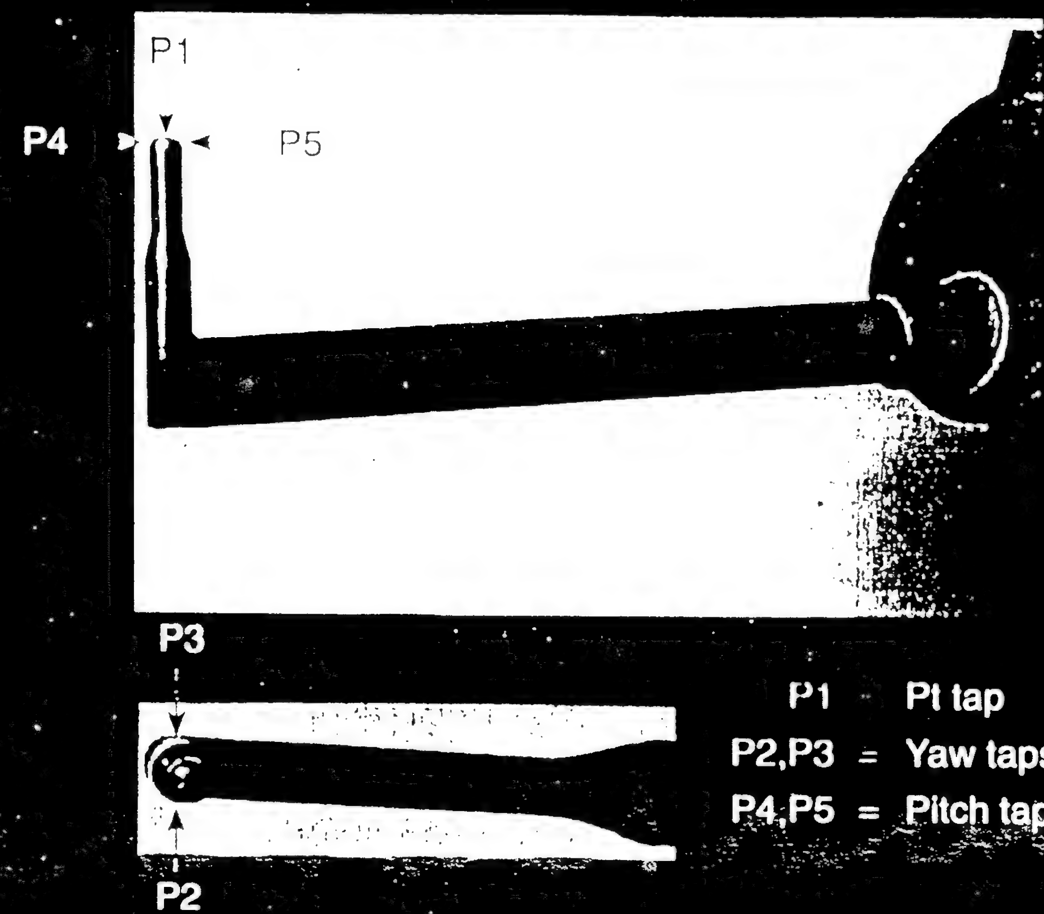


96A0006 071

5-HOLE SENSOR CALIBRATED WITH RESPECT TO FLOW ANGLE

The five measured pressures were reduced to four polynomials correlating:

1. Total pressure
2. Static pressure
3. Yaw angle
4. Pitch angle

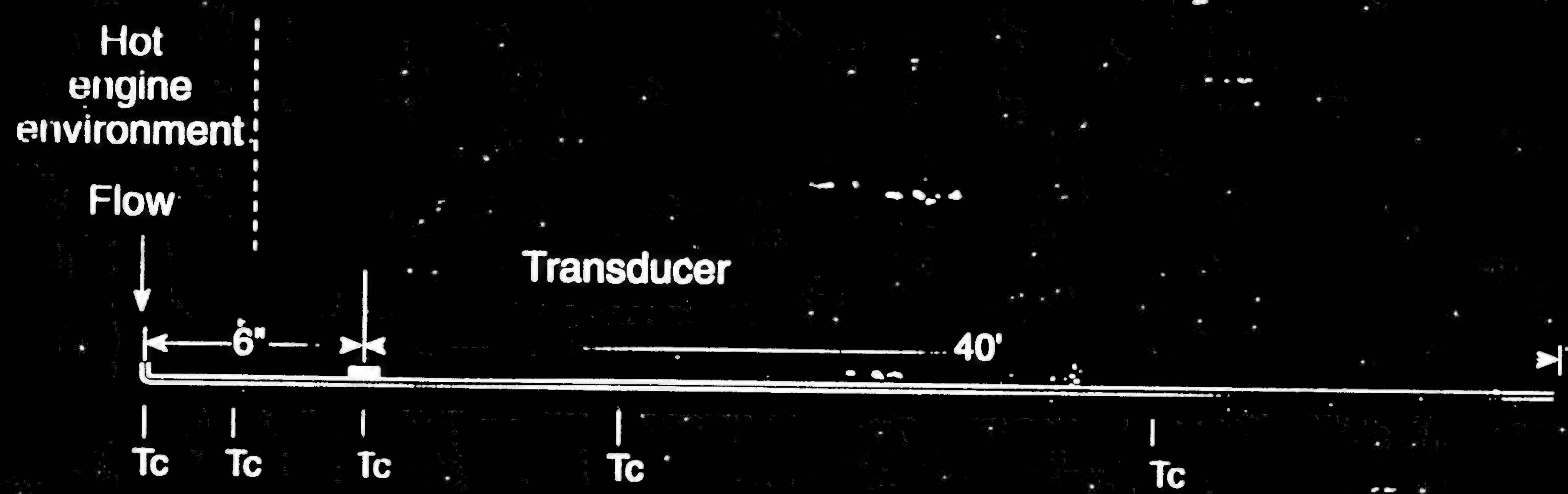


P1 = Pt tap
P2,P3 = Yaw taps
P4,P5 = Pitch taps

96A0606-060

IPT TECHNIQUE ALLOWS HIGH RESPONSE MEASUREMENTS WITH REMOTE TRANSDUCER

- Remote location provides nonhostile environment for pressure transducer

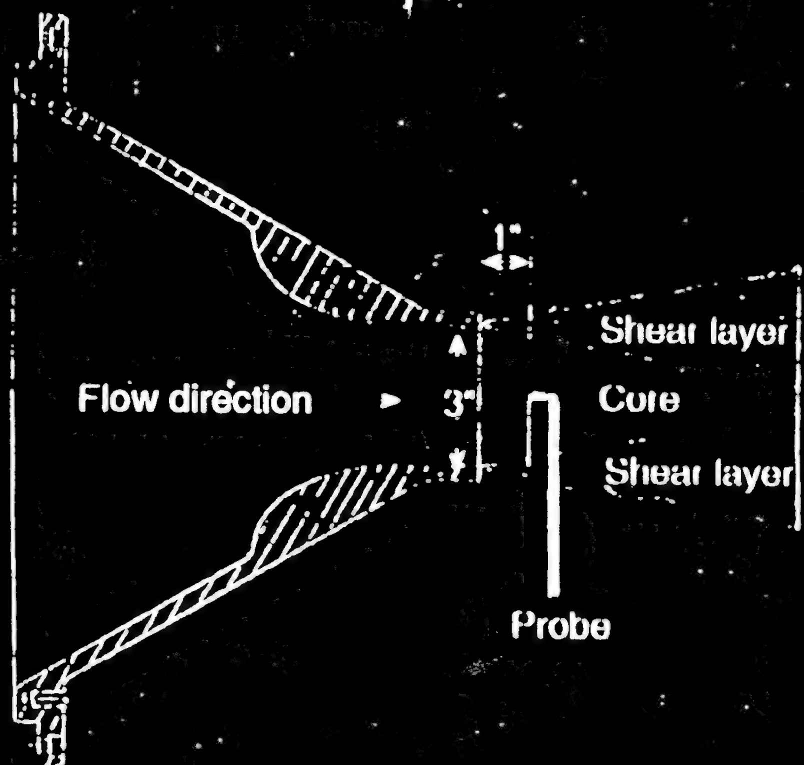


- Transducer pressures are corrected for attenuation in 6" sense tube

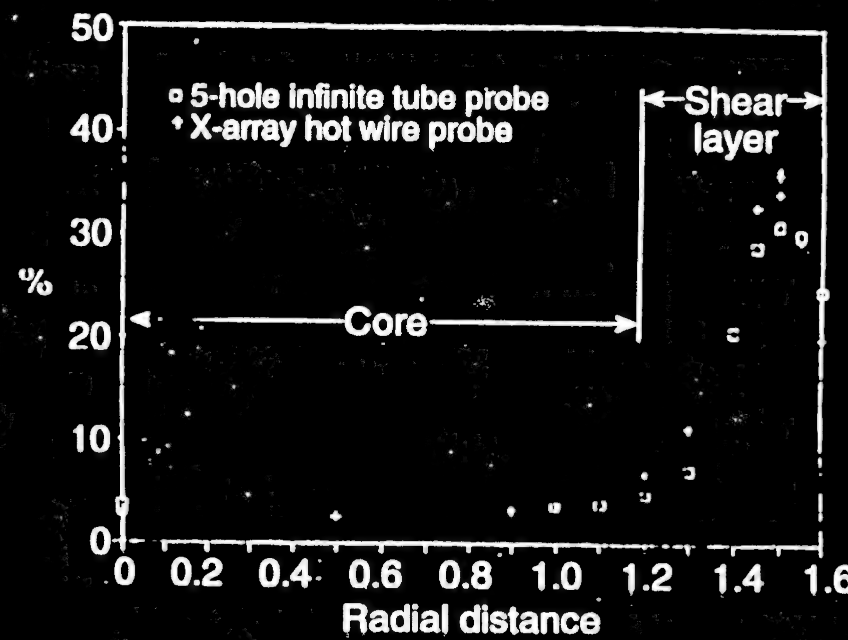
96A0606-061

AIR JET TURBULENCE CALIBRATION CONFIRMS ITP METHOD

Air jet

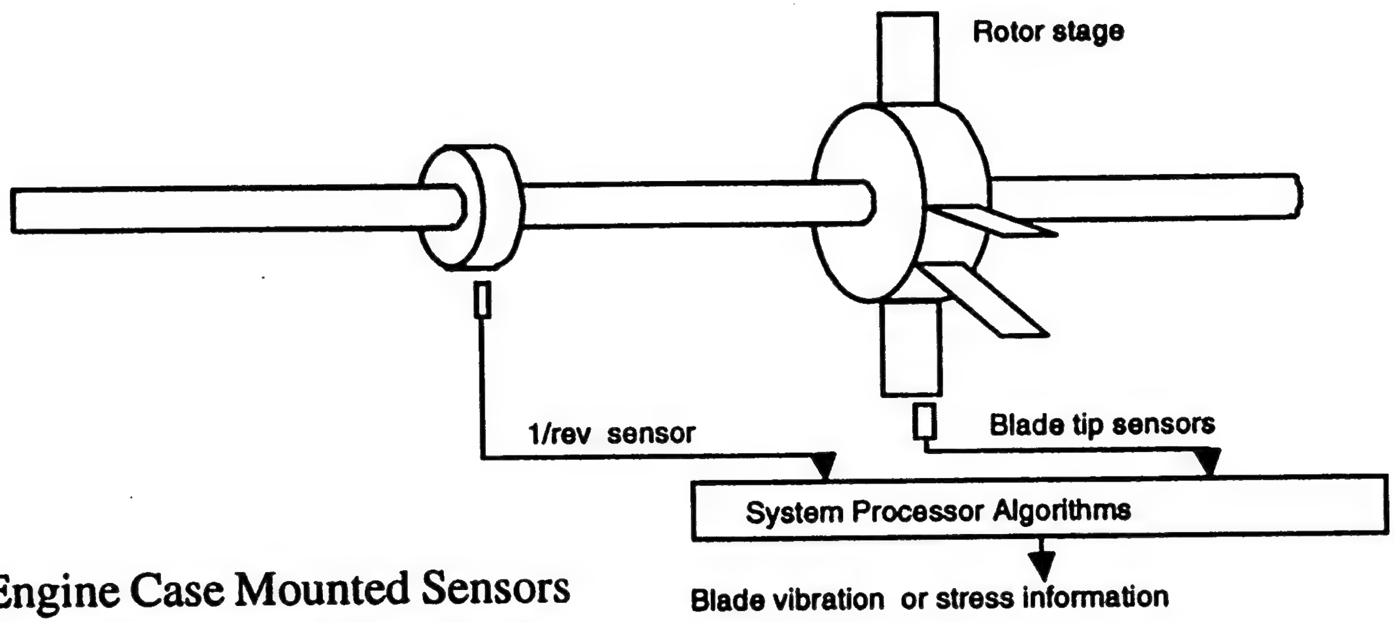


Turbulence



96A0606-064

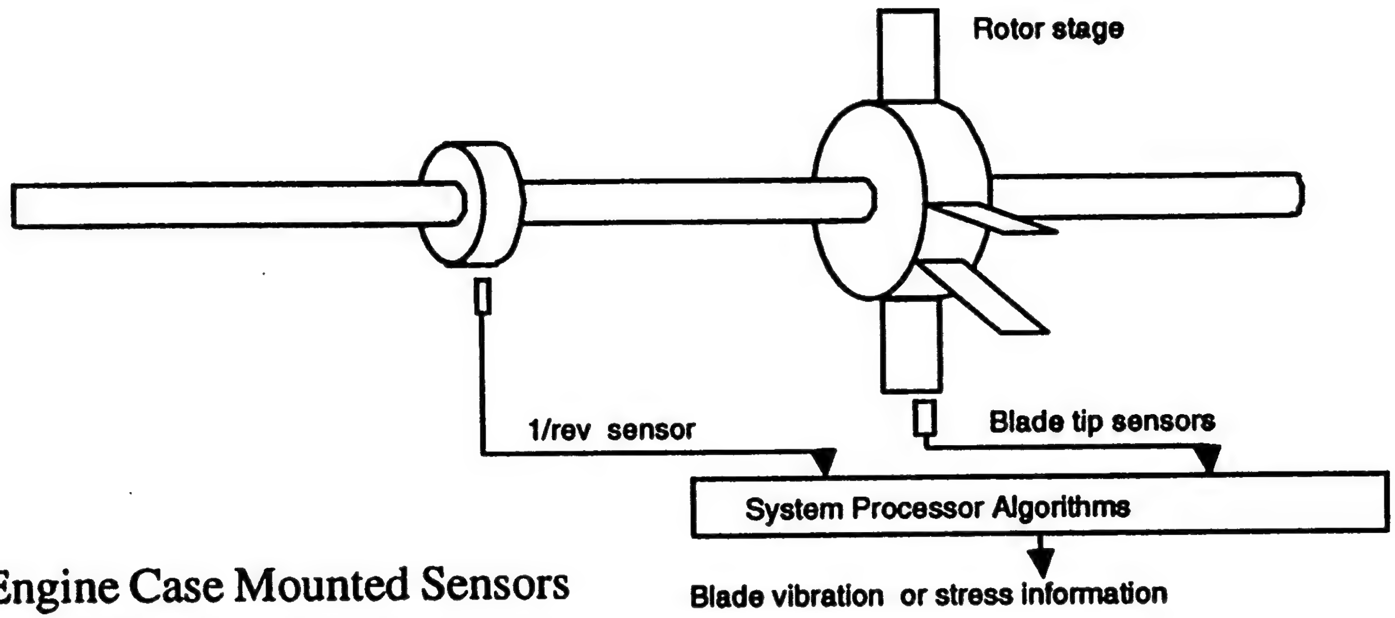
NSMS- *provides data on all blades*



- Engine Case Mounted Sensors
- Laser Illuminated Light Probes
- Blade Tip Deflection from Time of Arrival
- Data Processing to Extract Vibratory Components
- Displacement to Stress Conversion Algorithms

•Vibratory Response Via Variation in Time of Arrival Of the Blades Under Case Mounted Sensors

NSMS- *provides data on all blades*

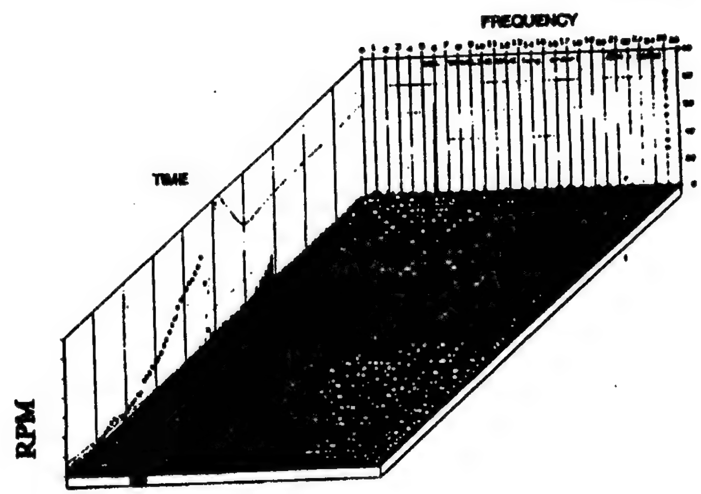


- Engine Case Mounted Sensors
- Laser Illuminated Light Probes
- Blade Tip Deflection from Time of Arrival
- Data Processing to Extract Vibratory Components
- Displacement to Stress Conversion Algorithms

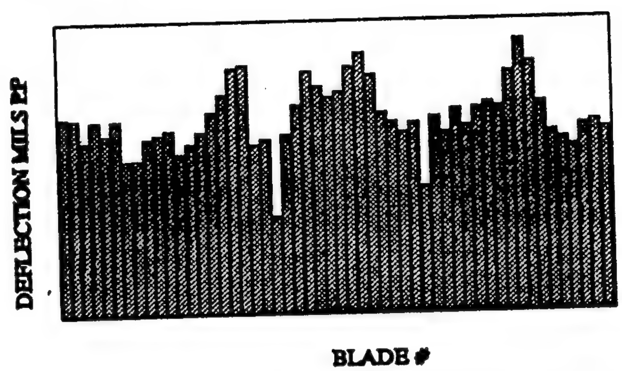
•Vibratory Response Via Variation in Time of Arrival Of the Blades Under Case Mounted Sensors

NSMS-

Typical Flutter Response On a Compressor Stage



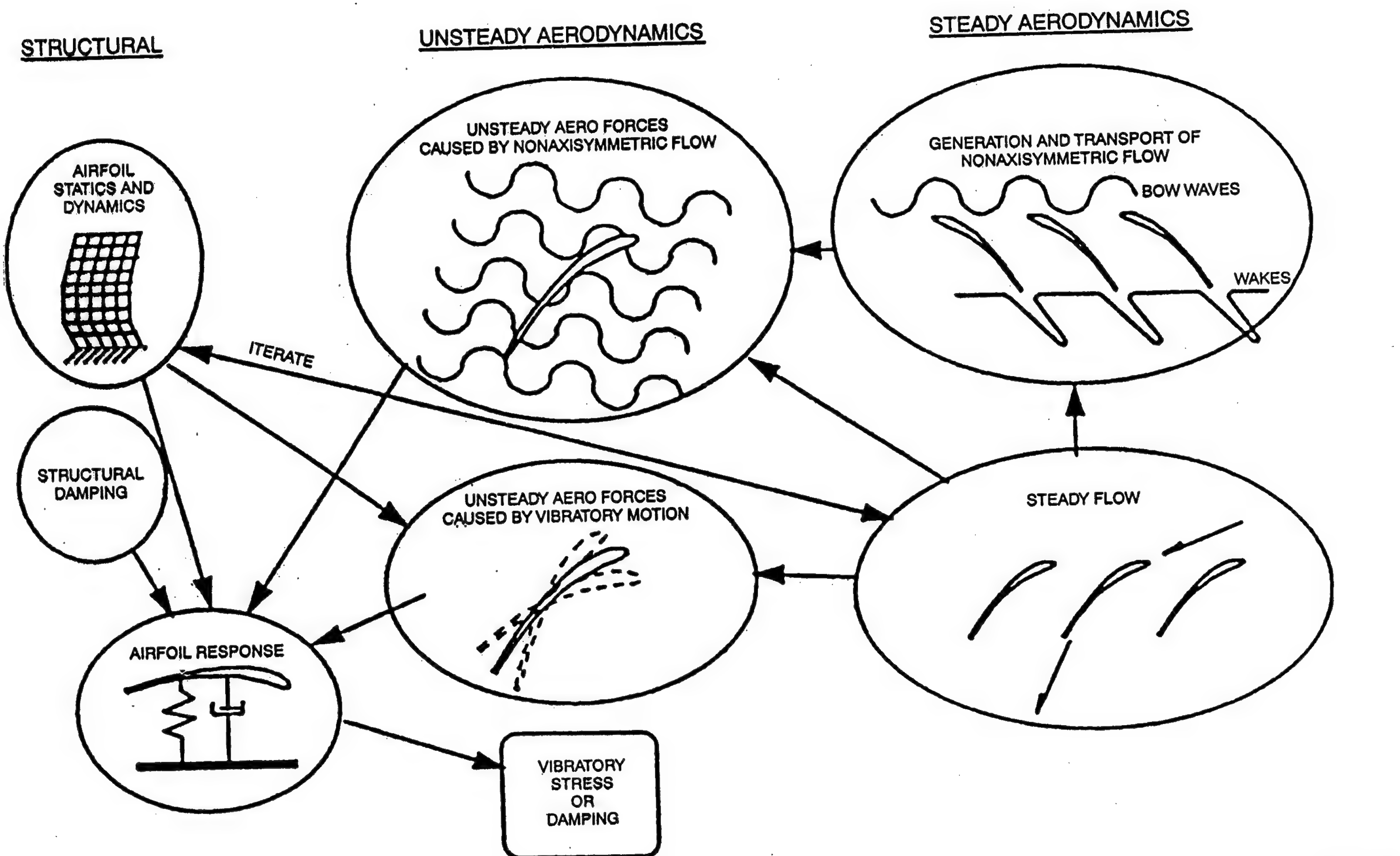
(a) Typical Flutter Response



(b) Blade-to-blade Amplitude Variation in Response

RESONANCE STRESS

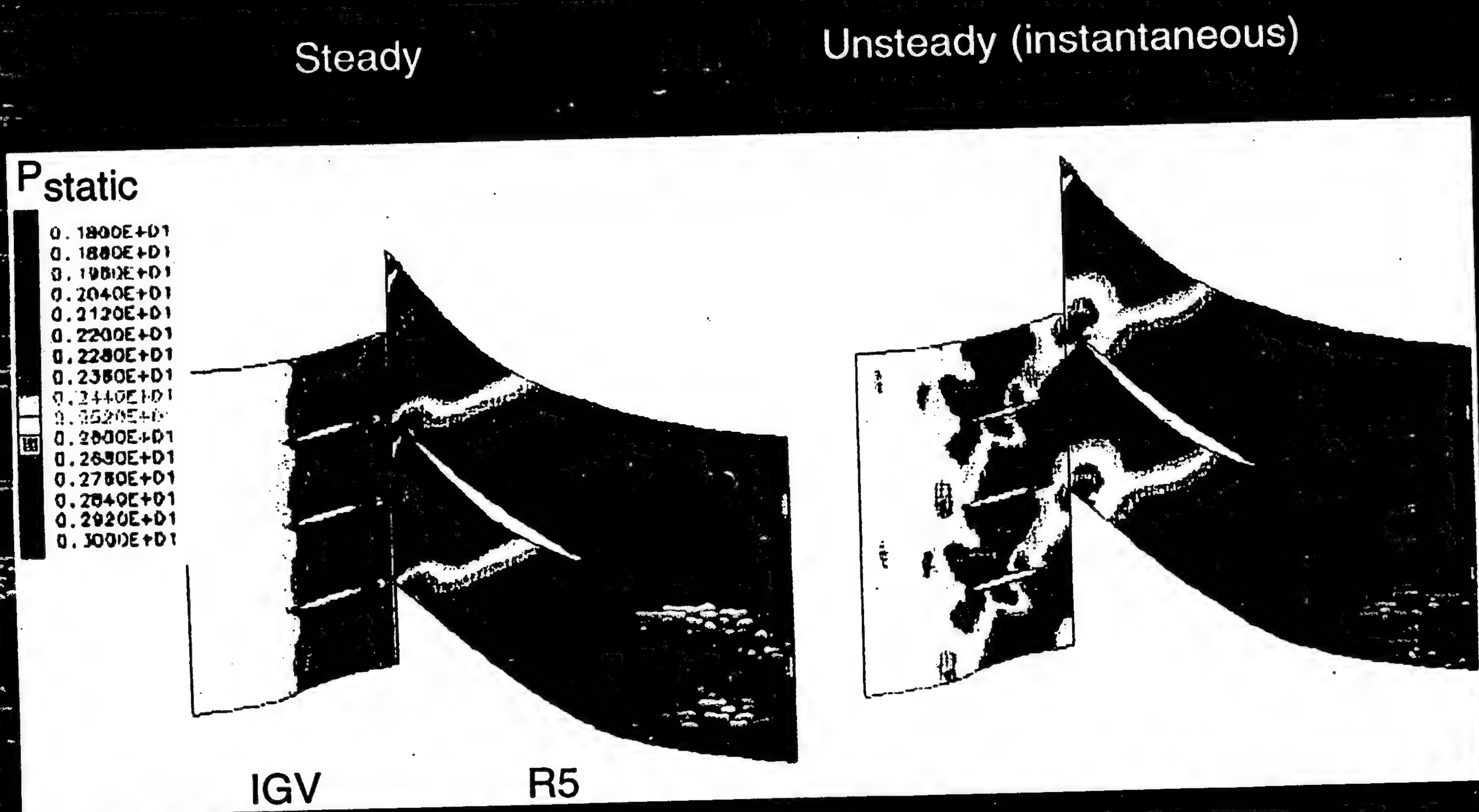
SCHEMATIC OF FORCED RESPONSE PREDICTION METHOD – HILBERT (1997)



S30500P-58

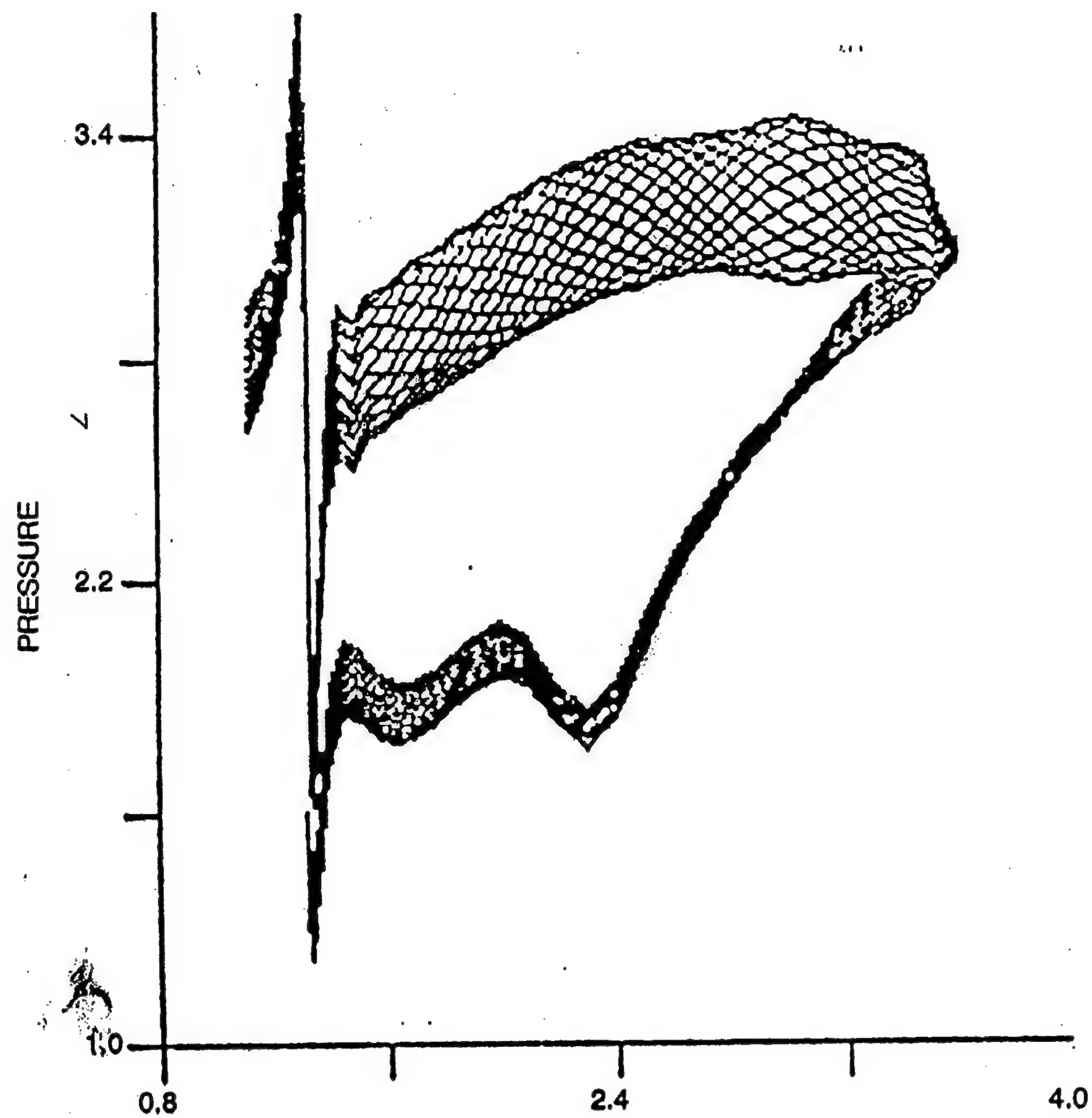
Figure 30a

UNSTEADY FLOW SIMULATIONS SHOW IMPORTANCE OF BLADE ROW INTERACTIONS



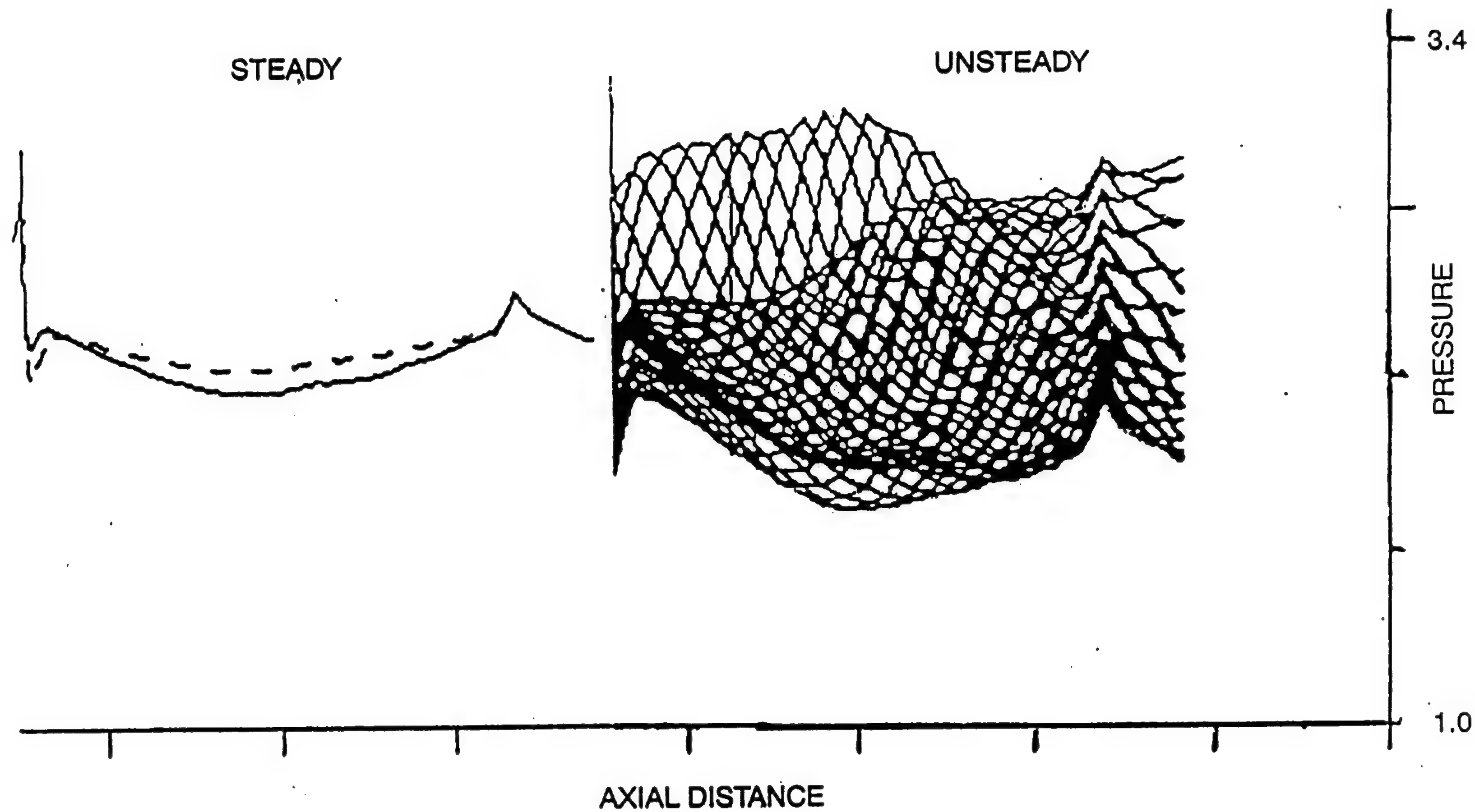
500-89 PULL FROM 96A0606-027

UNSTEADY PRESSURE ON THE ROTOR



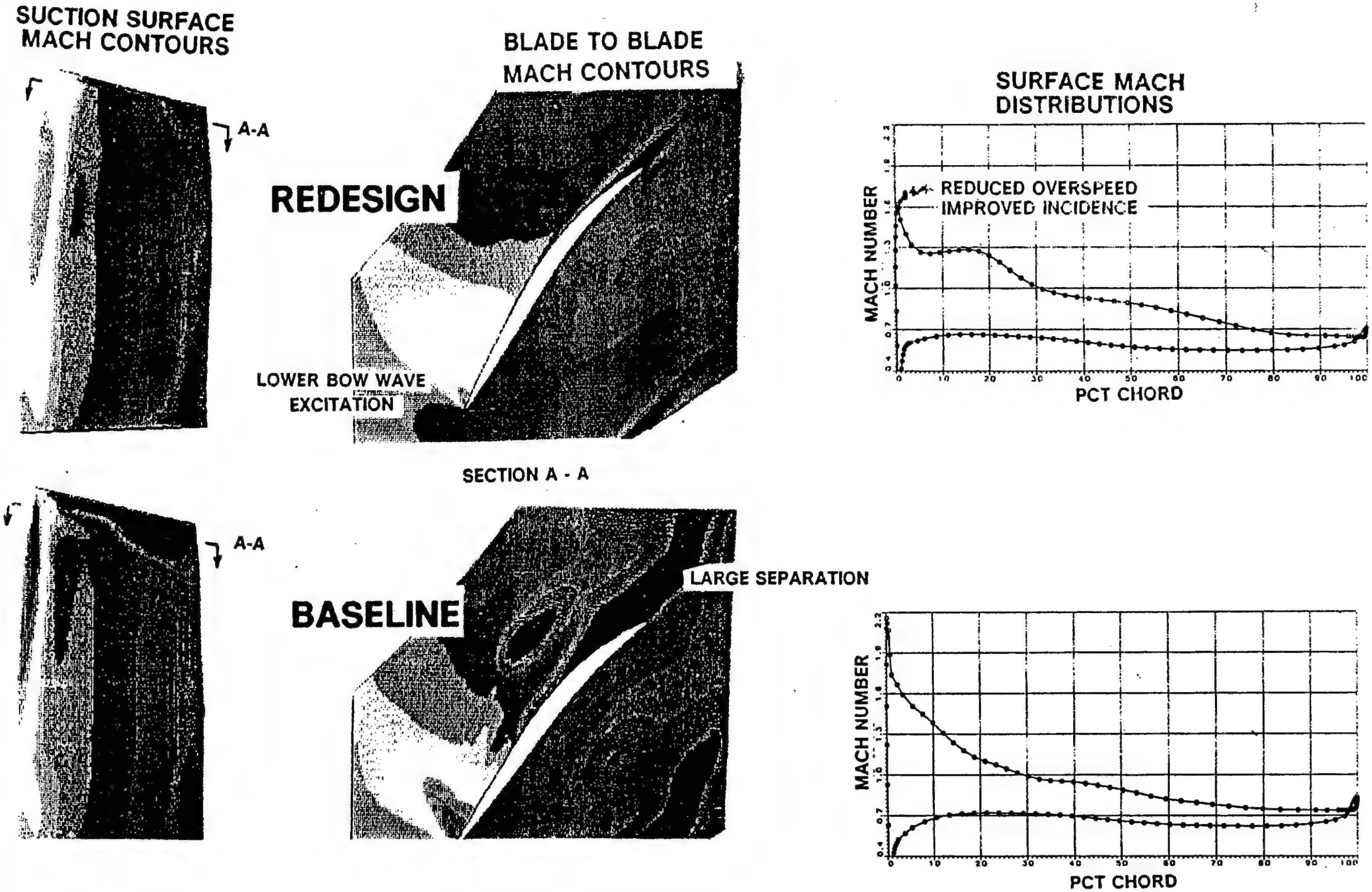
S30500P-88

HIGH LEVELS OF UNSTEADINESS PREDICTED FOR THE IGV DUE TO UPSTREAM EFFECTS FROM THE ROTOR



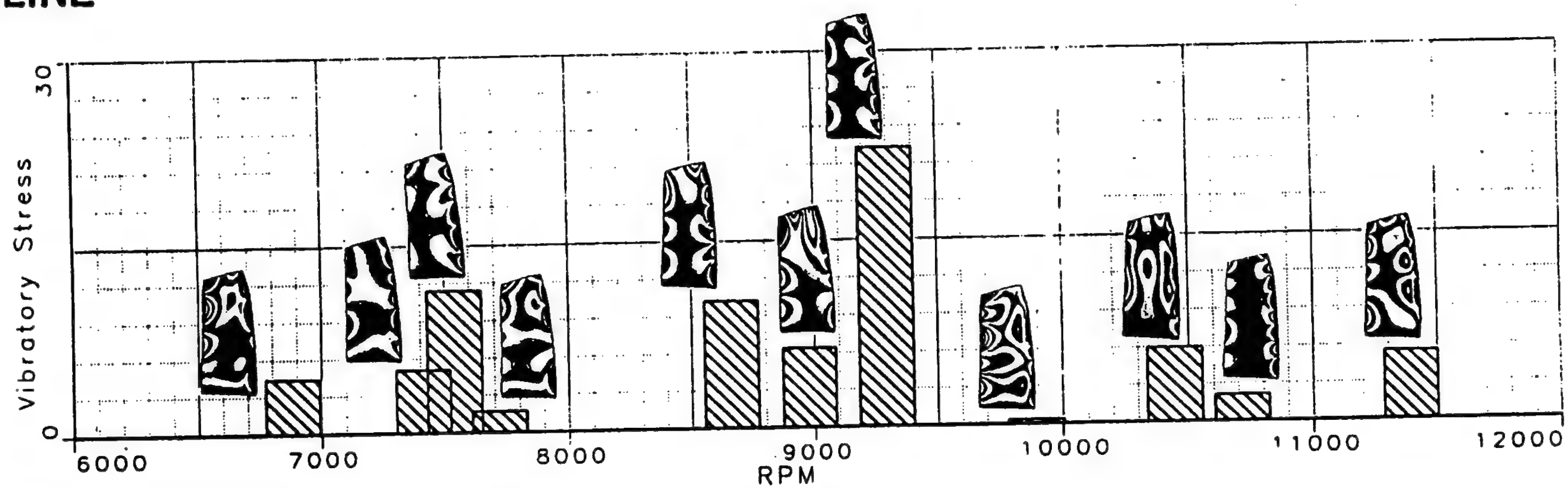
NASTAR CODE REDESIGNED ROTOR 5

- ELIMINATES SEPARATION
- REDUCES BOW WAVE EXCITATION

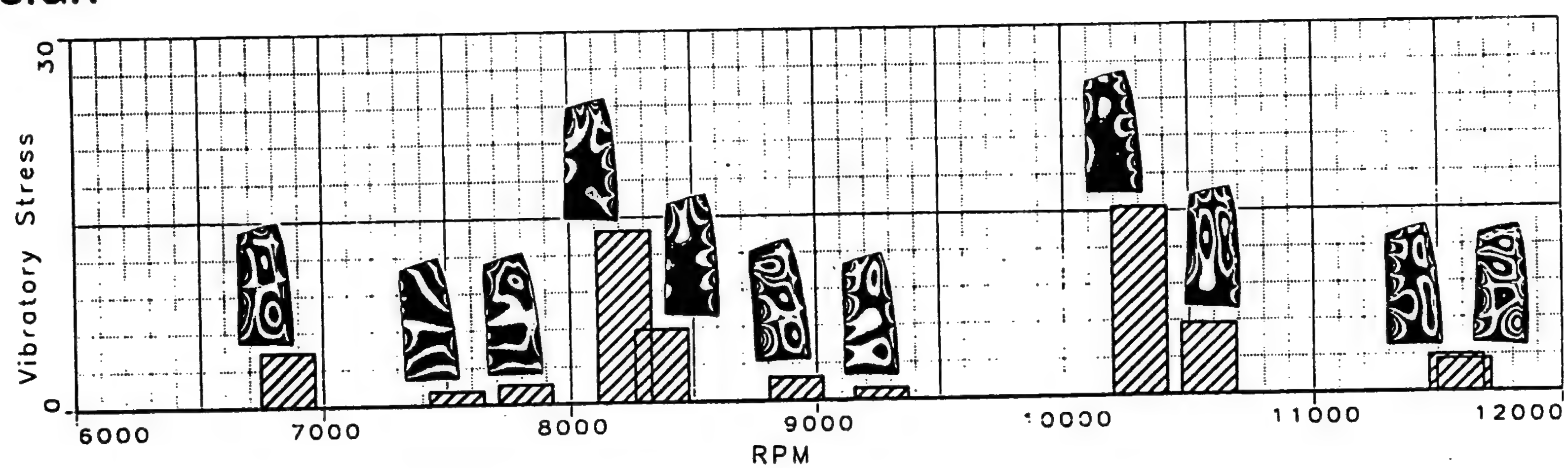


RESONANCE STRESS ANALYSIS IDENTIFIES HIGH RESPONDING MODE FOR BASELINE AND PREDICTS IMPROVEMENT FOR REDESIGN

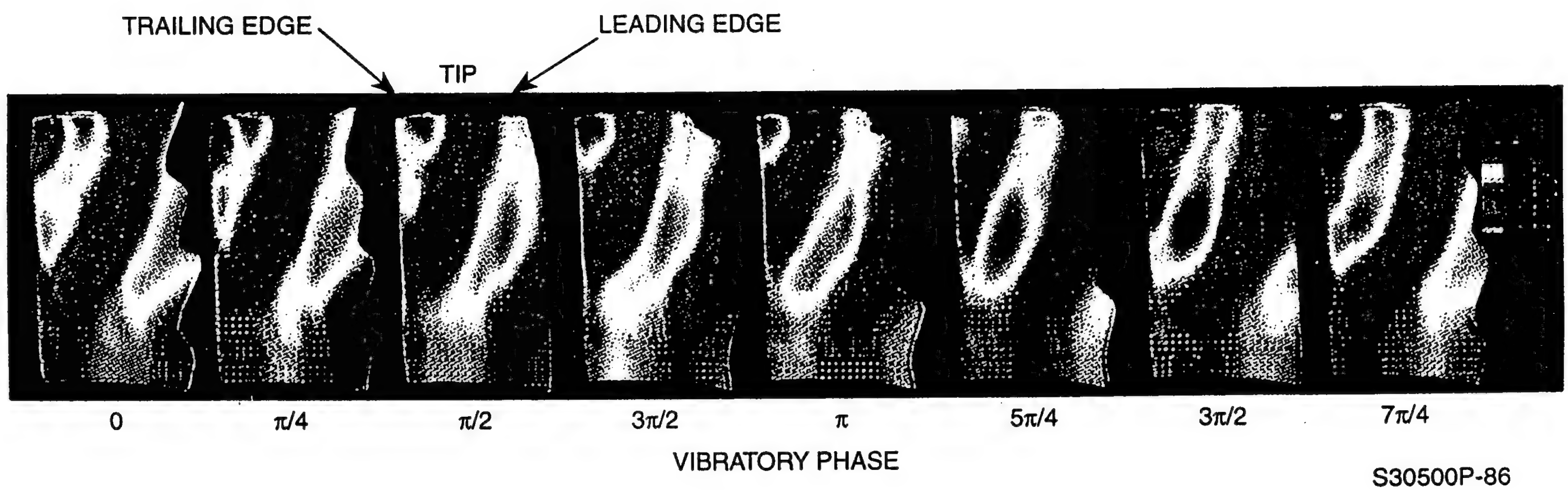
BASELINE



REDESIGN



ROTOR MAXIMUM RESPONSE TO IGV EXCITATION OVER ONE VIBRATORY CYCLE



VIBRATORY DEFLECTIONS IS EXAGGERATED AND UNSTEADY SURFACE PRESSURE IS ON PRESSURE SIDE OF AIRFOIL – HILBERT (1997)

S30500P-86

FLUTTER

FLUTTER AND SURGE/STALL

- **Flutter**
  - An aeromechanical instability
  - Depends on aero, structural, and mechanical damping
- **Surge/Stall**
  - Hydrodynamic instability of pumping systems
  - Depends only on aerodynamic system damping

FLUTTER AND SURGE
- Common Operational Considerations -

- These problems are
  - Dangerous (engine damage and aircraft loss)
  - Common (one or the other appear in every engine line)
  - Major influence on readiness
- Events can occur in isolated parts of flight envelope
- Problems appear both
  - In development
  - In the field
- Worn engines may have different stability than new engines
- Sensitive to small manufacturing and maintenance variations
- These are difficult and very expensive problems to fix
- Large maintenance loads result

FLUTTER AND SURGE
- Common Engineering Behavior -

- Complex modal behavior
  - Many modes potential participants
  - Lowest order modes often the most important
- Difficult to predict stability boundaries from first principles
  - Empirical correlations used in practice
  - Correlations not always reliable
- Poor predictive capability dictates large engineering margins
  - Extra compressor stages for surge
  - Thicker airfoils, lower efficiency for flutter
- Engines can tolerate only a few seconds of these instabilities
- Engineering fixes often decrease efficiency
- These instabilities are amenable to active control

FLUTTER AND SURGE – CONTRASTS

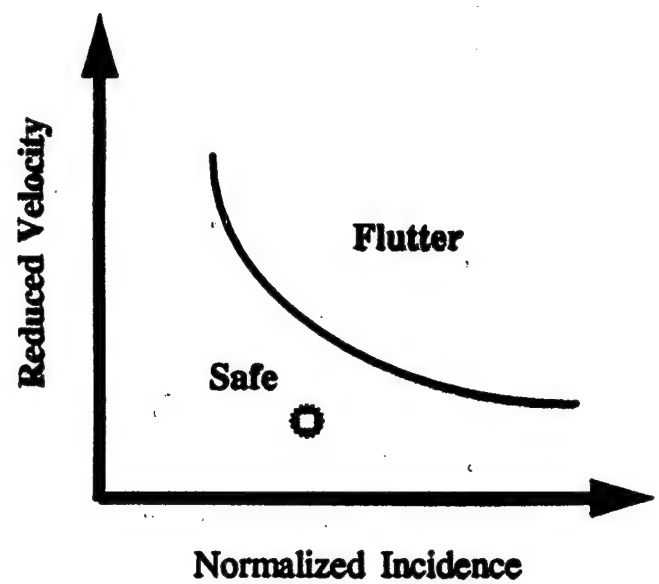
- Physics
  - Surge - depends only on aero system damping
  - Flutter - depends on both aero and mechanical damping
- Damping variation from normal op. pt. to instability
  - Surge - aero damping large at op. pt. drops to zero, large variation
  - Flutter - aero damping always small, small variation
- Susceptible components
  - Surge - compressor system only
  - Flutter - compressor and turbine
    (seals subject to aeroacoustic instabilities)
- Pilot awareness
  - Surge - apparent when it occurs
  - Flutter - unapparent until inspection or failure

Flutter Analysis

Empirical methods are no longer adequate - Robust CFD approaches needed for Stall Flutter predictions

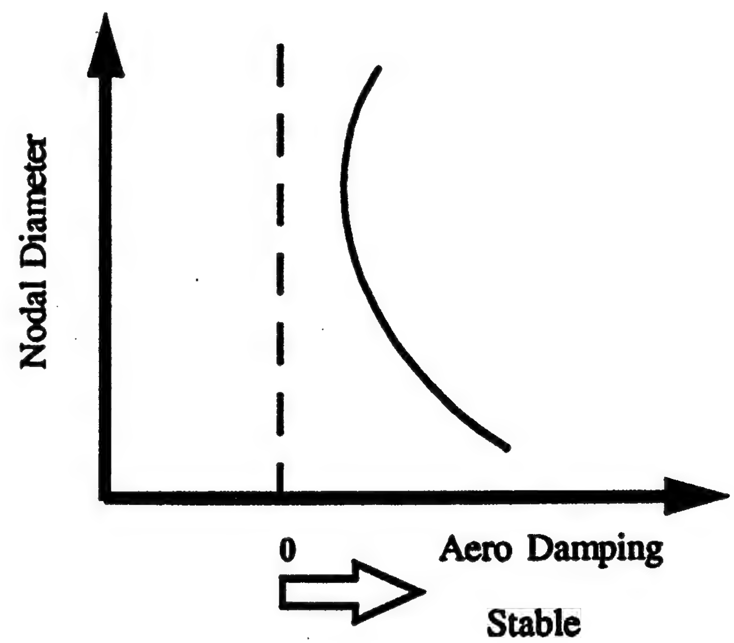
Empirical System

(Two parameter correlations)



Analytical System

(Semi-Empirical and CFD Based Approach)



Damping

ESSENTIAL for controlling system response

Sources:

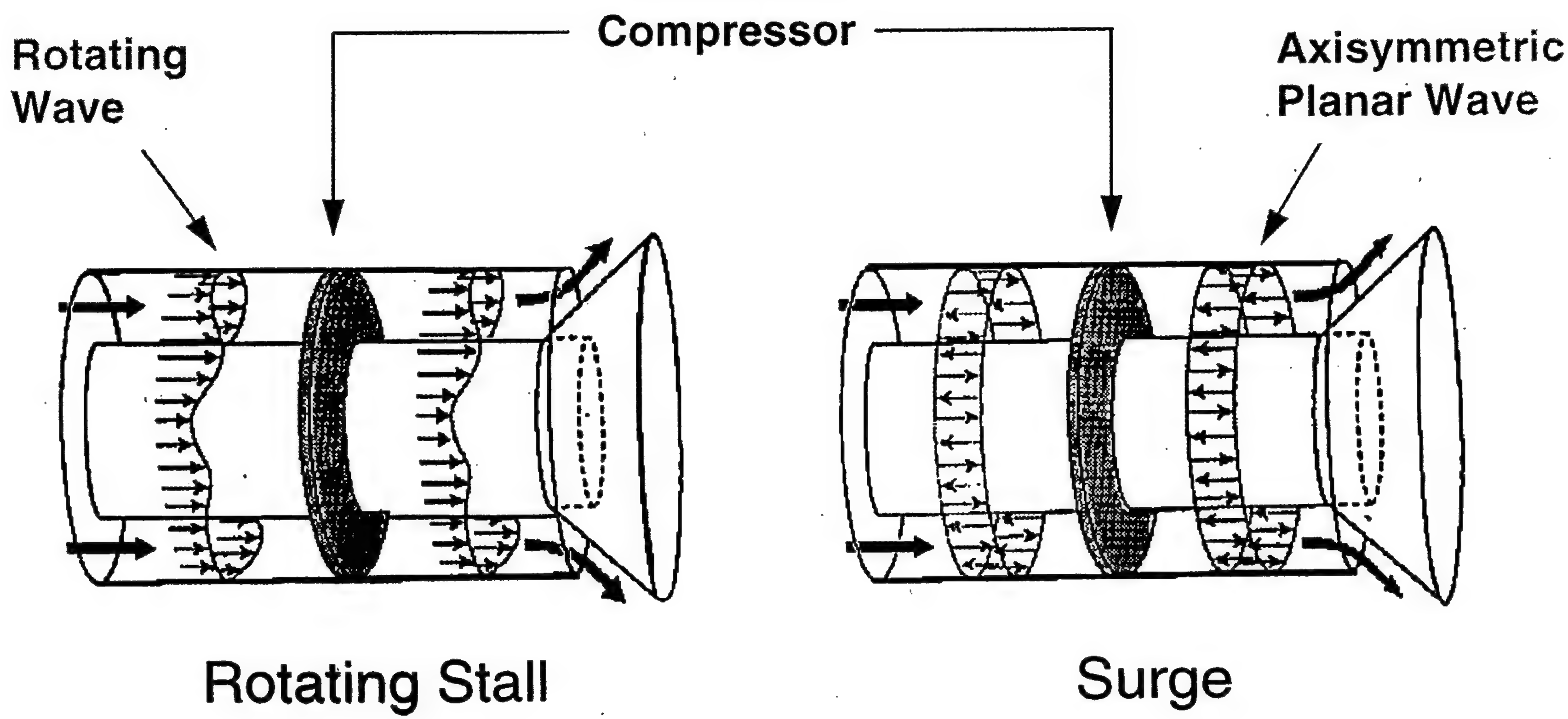
- <u>***Structural***</u> *(shrouds, attachments, platform dampers, ring dampers, internal dampers, constrained layer viscoelastic, particle dampers)*
- <u>***Aerodynamic***</u> *(small BUT Critical)*
- <u>***Material***</u> *(small)*

STABILITY

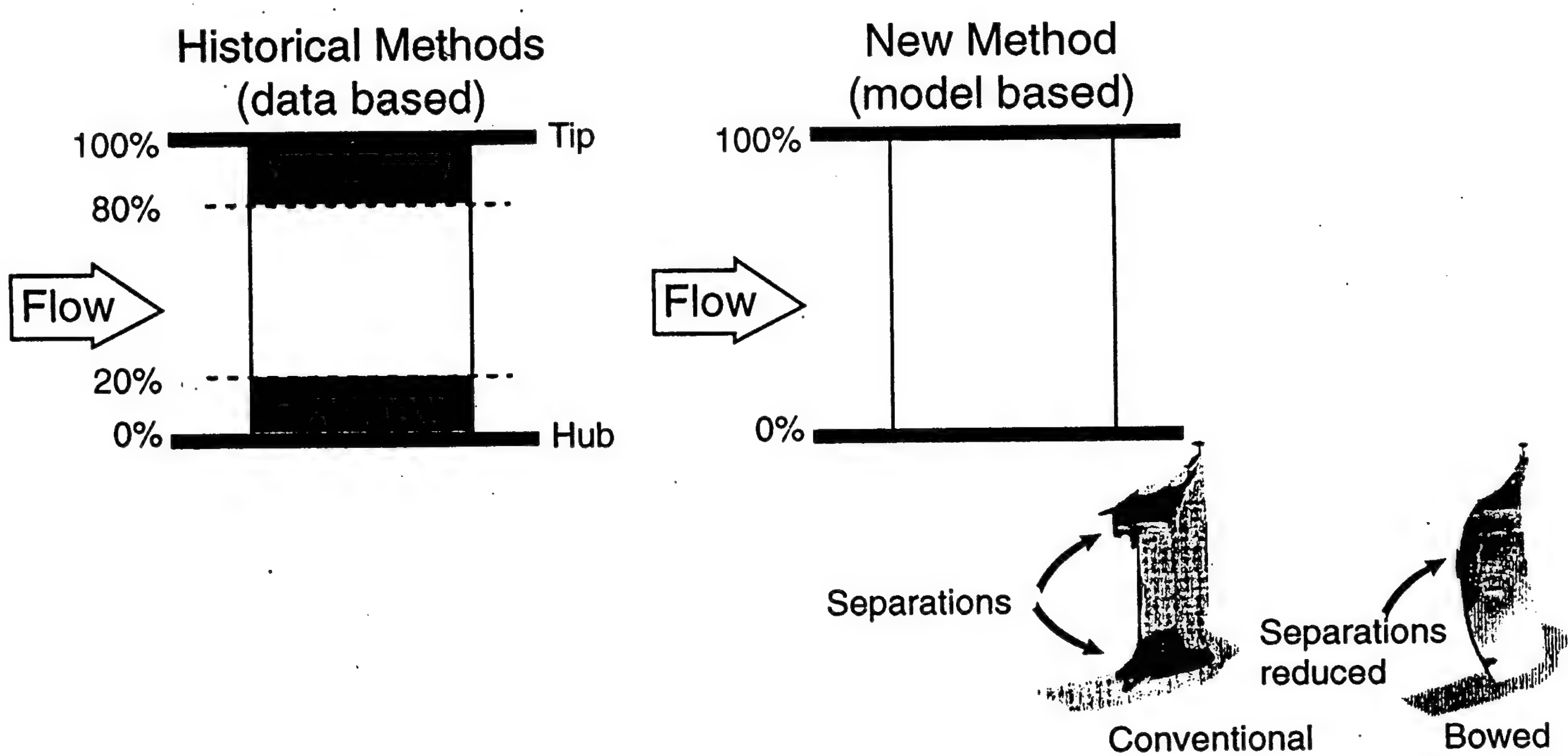
ONE HISTORICAL VIEW OF COMPRESSOR INSTABILITIES

	Problems	Inventions	Theories
1940	Whittle Engine (Surge)	Bleed	
1950	J-79 (Surge)	Multiple Spools Variable Geometry	Emmons (Basic Concepts) Marble (Linear Theory)
1960	TF-30 (Surge)		
1970	JT9D (Rotating Stall)	Casing Treatment	Ploude (Distortion)
1980	F-100 (Nonrecoverable Stall)		Greitzer (Surge)
			Moore & Greitzer (Rotating Stall)
		Active Control(?)	

Compressor Oscillatory Modes



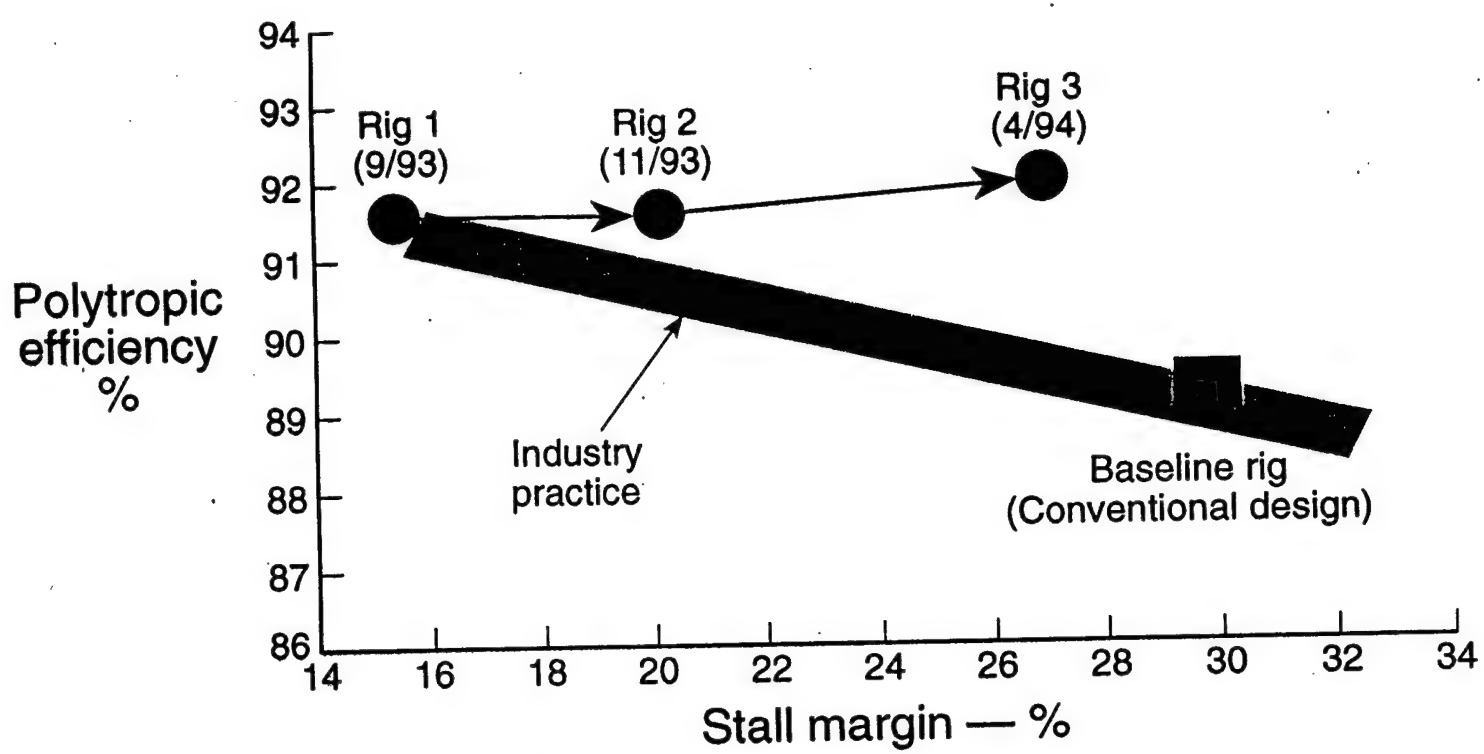
DESIGN/OFF-DESIGN FLOW PREDICTION SYSTEM



- NASA LeRC provided rigorous framework for modeling
- Networking of workstations provided enabling technology

PROGRESS — DESIGN/OFF-DESIGN PREDICTION

PW409X HPC DEVELOPED BY UTILIZING THE CFD CODE

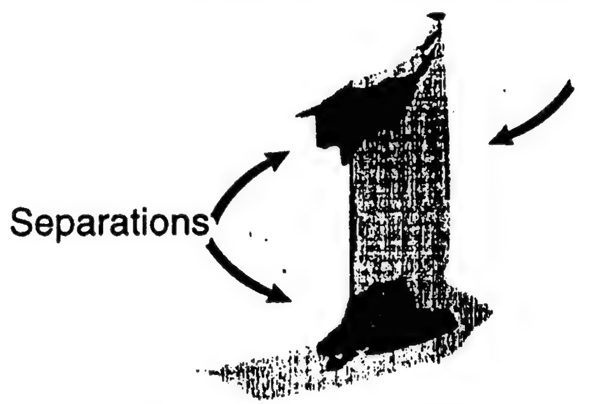


- State-of-the-art changed
- Stability of the compressor achieved by a combination of the "new" and "old" techniques

STABILITY PREDICTION SYSTEM

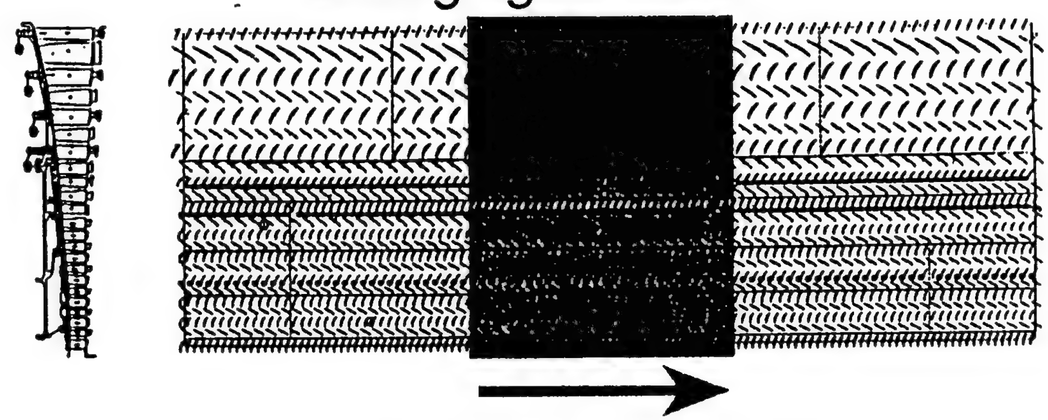
FLOW PHYSICS GOVERNED BY HYDRODYNAMIC INSTABILITY OF PUMPING SYSTEMS

Historical Methods



Stability governed by flow separation on airfoils

Emerging Methods



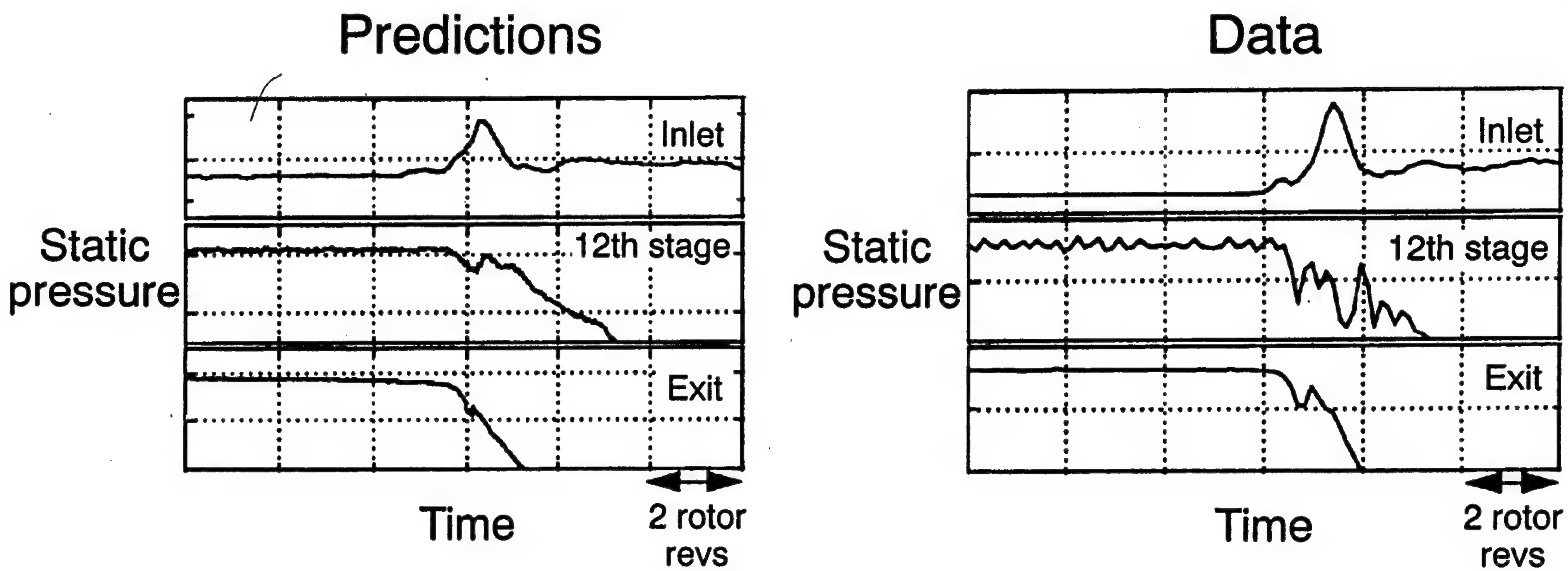
Rotating disturbance

Stability governed by unsteady flow of the order of compressor lengths

Moore (Cornell), Greitzer (MIT) provided rigorous framework

PROGRESS — STABILITY PREDICTION

2D UNSTEADY DYNAMIC STABILITY PREDICTION SYSTEM VERIFIED AGAINST 11 STAGE RIG DATA



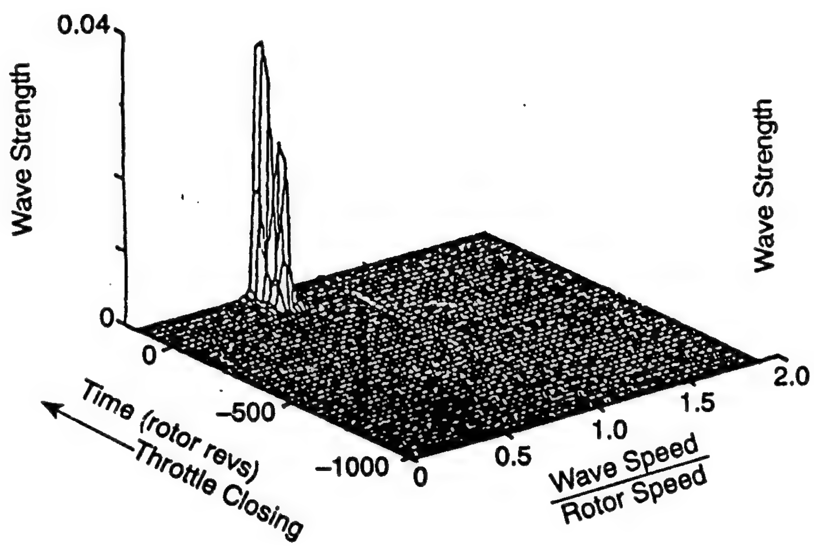
System used to assist in enhancing HPC stability through vane schedules, bleed flow and axial work distribution management

PROGRESS — STABILITY PREDICTION/CONTROL

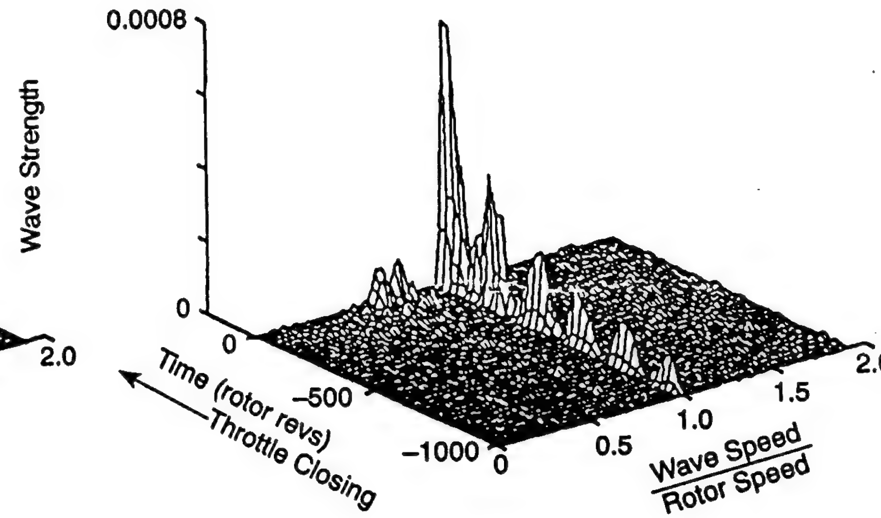
➡ New stall "precursors" identified at P&W (9/93)

➡ Existence of "precursors" confirmed by the stability prediction method (11/93)

Scale Set for Stall



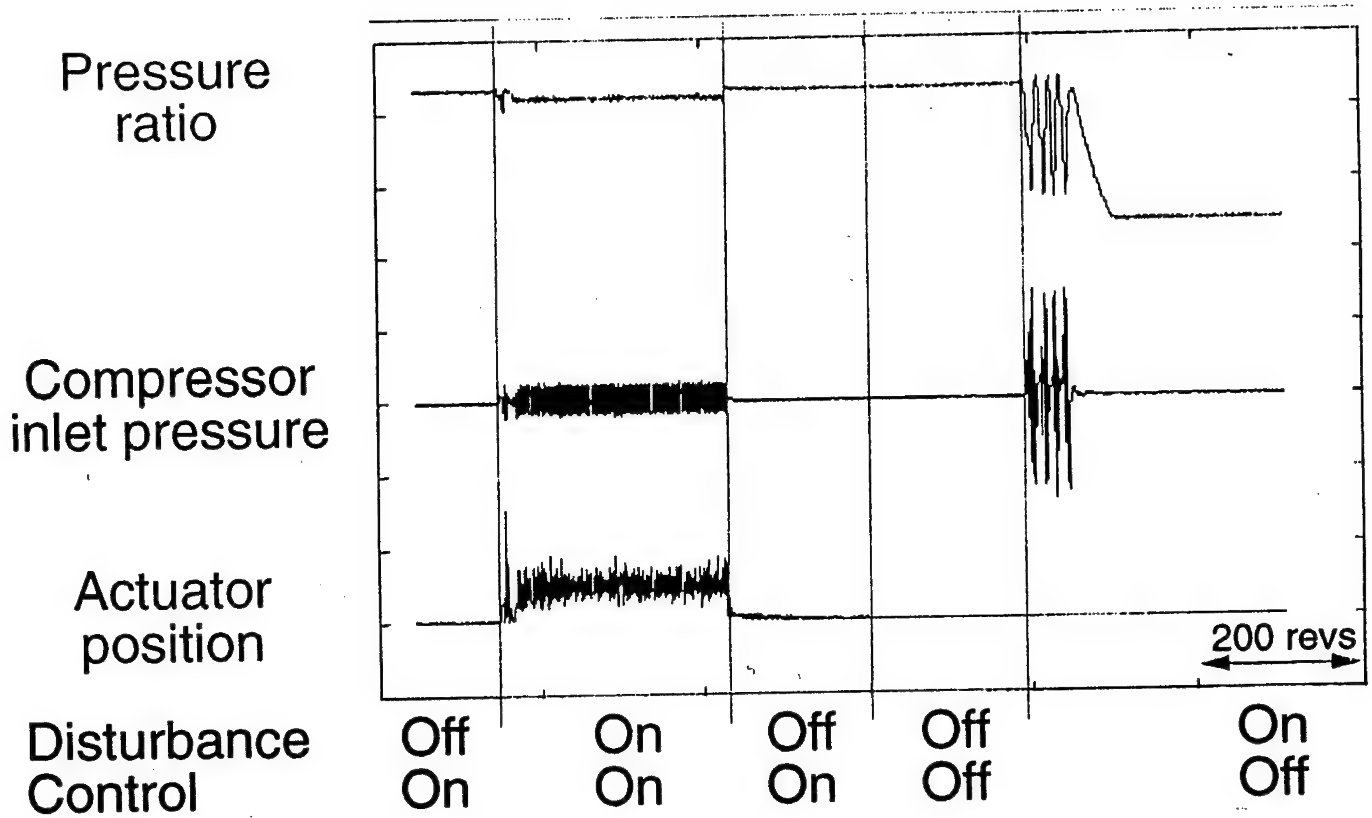
Expanded Scale

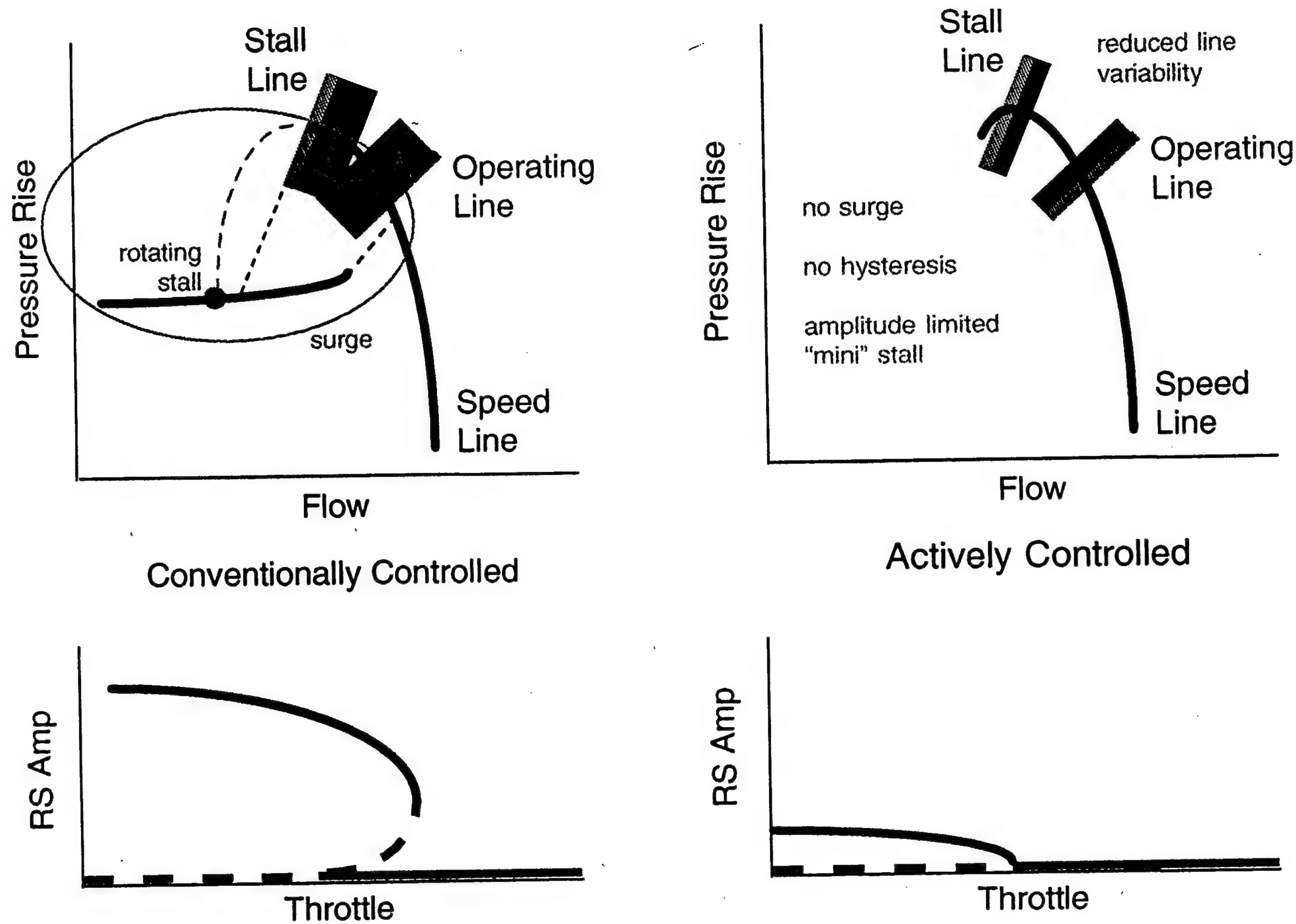


- MIT paper (6/94) also shows "precursors" in 11 compressors

PROGRESS — STABILITY CONTROL

ACTIVE STABILITY CONTROL CONCEPT DEMONSTRATED IN A 3-STAGE RIG





Stall Line
Operating Line
Speed Line
rotating stall
surge
Pressure Rise
Flow
Conventionally Controlled
RS Amp
Throttle
Stall Line
reduced line variability
Operating Line
Speed Line
no surge
no hysteresis
amplitude limited "mini" stall
Pressure Rise
Flow
Actively Controlled
RS Amp
Throttle

SUMMARY

- PREDICTION SYSTEMS DEVELOPED BASED ON 3D, STEADY, RANS CODES TO PROVIDE REASONABLE DESCRIPTION OF TIME-AVERAGED FLOWS IN A MULTISTAGE ENVIRONMENT
  - Useful in controlling separation and stage matching for conventional designs
- UNSTEADY RANS AND FLARES CODES DEVELOPED
  - Useful in simulating effects of periodic unsteadiness
- 3D LINEARIZED CODES DEVELOPED FOR FLUTTER AND RESONANCE STRESS PREDICTIONS
- 2D LINEAR AND NON-LINEAR CODES DEVELOPED FOR STABILITY PREDICTION
- INSTRUMENTATION AND DATA PROCESSING TECHNIQUES DEVELOPED TO MEASURE DEFLECTION & PRESSURES IN AN ENGINE ENVIRONMENT

FUTURE DIRECTION

- MODELS TO CAPTURE UNSTEADY EFFECT INDUCED BY TURBULENCE
  - LES IN RANS CODES
- INCREASE UTILIZATION OF UNSTEADY RANS CODES
- RIGOROUSLY ACCOUNT FOR THE EFFECTS OF BLADE MOTION ON AERODYNAMICS
- QUANTIFY EFFECTS OF VISCOSITY ON FLUTTER
- DEVELOP DATA MINING & KNOWLEDGE EXTRACTION TOOLS TO INTERROGATE RESULTS FROM NUMERICAL SIMULATIONS RIGOROUSLY

Active Control of Rotating Stall Using Pulsed Air Injection

Richard M. Murray

Caltech/UTRC

Outline

I. Overview of AFOSR PRET Center on Nonlinear Control of Stall and Flutter in Aeroengines

II. Bleed valve control of rotating stall: magn/rate effects

III. Control of rotating stall using pulsed air injection

IV. Summary and conclusions

Presentation at the Gas Turbine Workshop
Atlanta, GA, June 15-16, 1998

Dynamics and Control of Compression Systems

AFOSR PRET Center

Robust Control of Stall, Surge and Flutter in Aeroengines

Petar Kokotovic	Art Krener	Richard Murray	Jim Paduano	Gonzalo Rey
UCSB	UC Davis	Caltech	MIT	UTRC

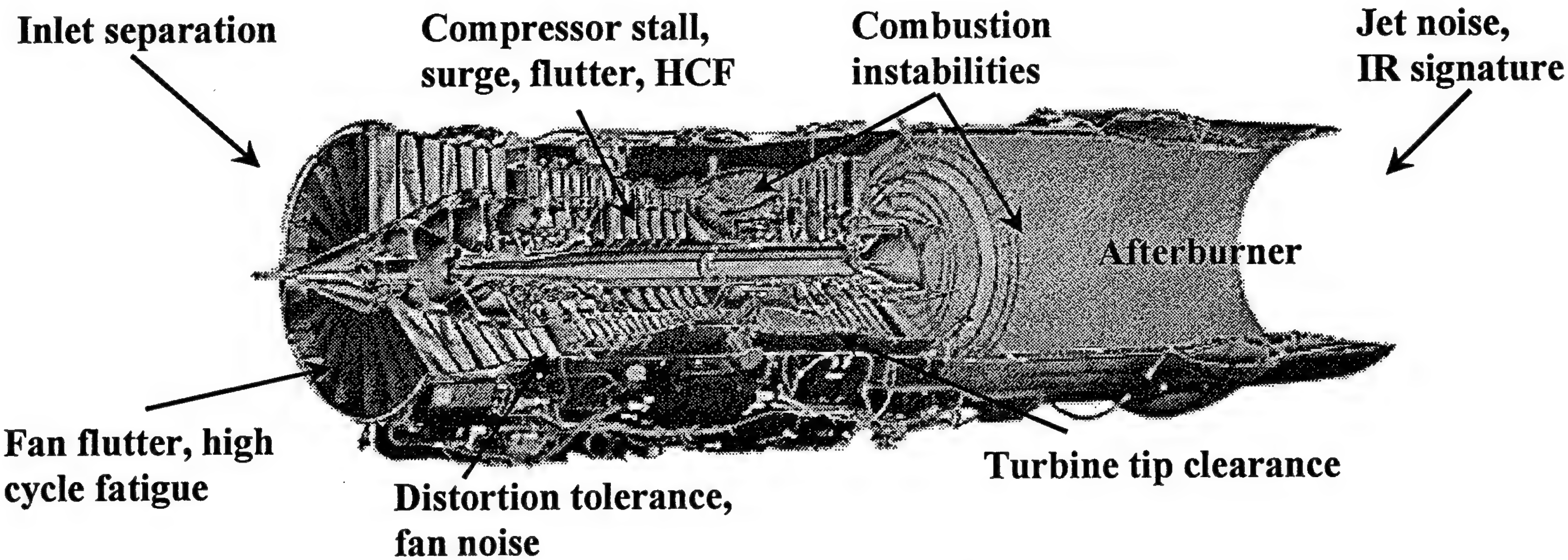
Raff D'Andrea Robert Behnken Simon Yeung Brianno Coller
Yong Wang Sean Humbert Asif Khalak Mina Leung

http://avalon.caltech.edu/~compress

AFOSR • PRET
Partnership for Research Excellence & Transition

UCSB • UCDavis • CalTech • MIT • UTRC

Performance Limitations in Aircraft Engines



Inlet separation
- Separation of flow from surface
- Possible use of flow control to modify

Distortion
- Major cause of compressor disturbances

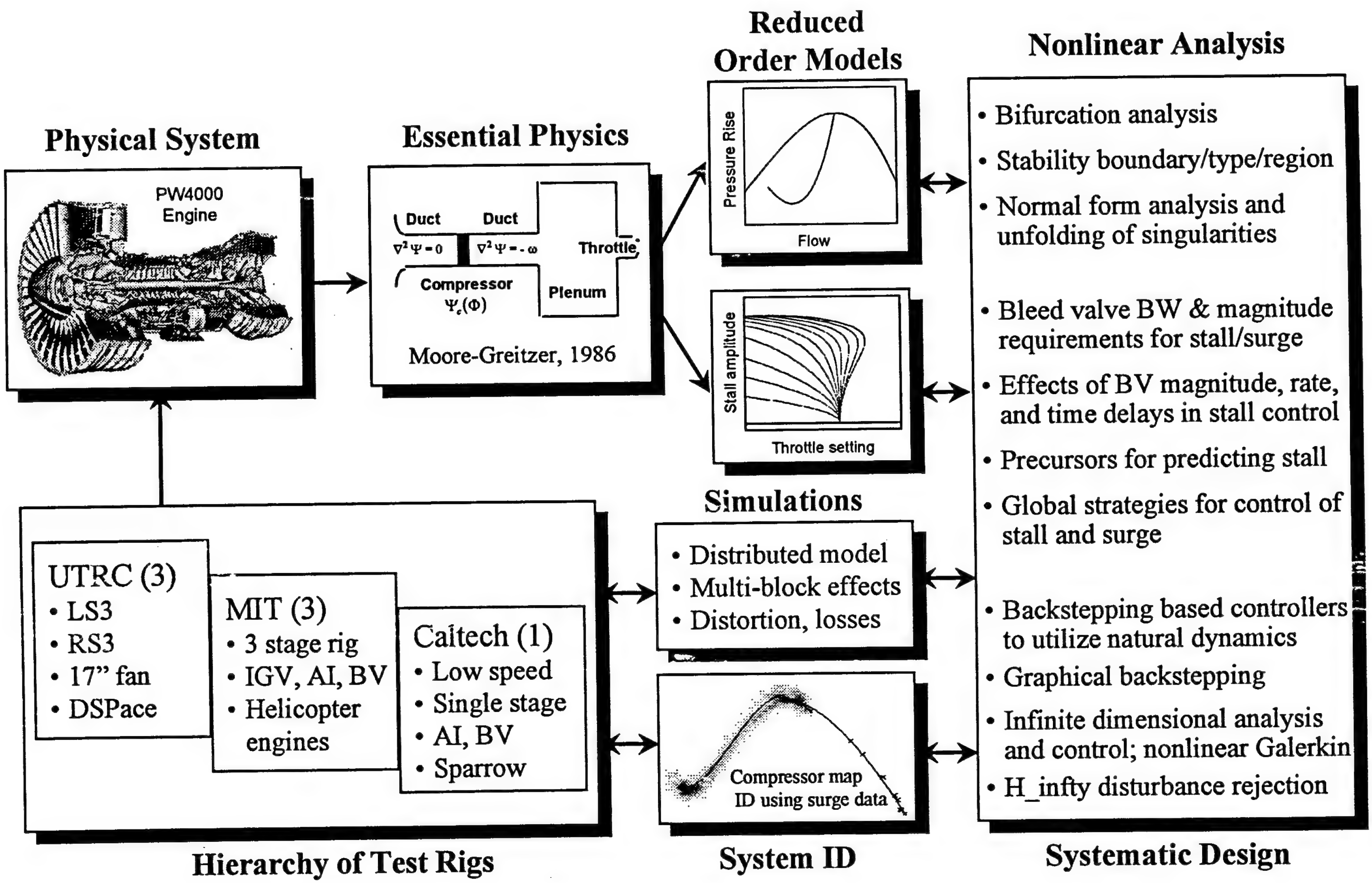
Rotating stall and surge
- Control using BV, AI, IGVs demonstrated
- Increase pressure ration ⇒ reduce stages

Flutter and high cycle fatigue
- Stability (flutter) and forced response (HCF)
- Linear control (MIT; on/off blade), forced response using evalues/evectors (Caltech/Shapiro)

Combustion instabilities
- Large oscillations cannot be tolerated
- Typically discovered late in development

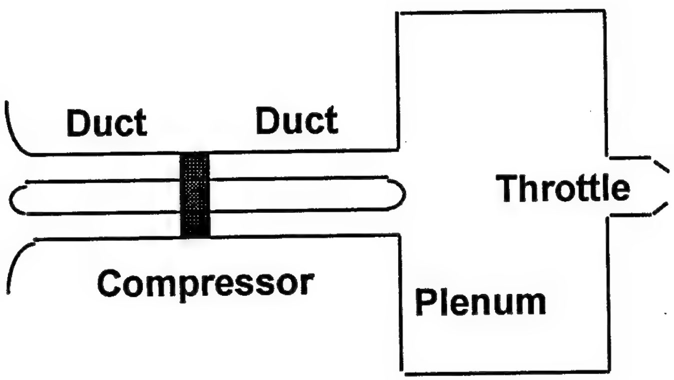
Jet noise and shear layer instabilities
- Gov't regulations driving new ideas

Control Design Philosophy for Stall/Surge/Flutter

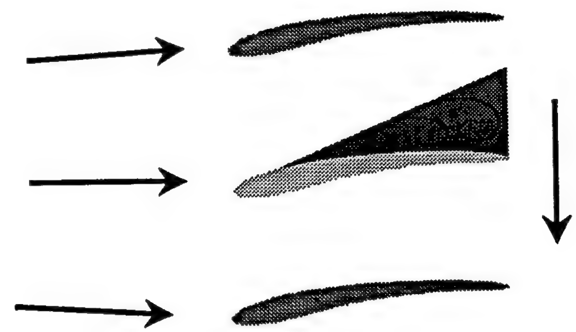


R. M. Murray, Caltech/UTRC

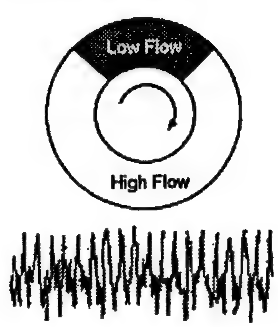
Rotating Stall and Surge



Emmons model (1952)

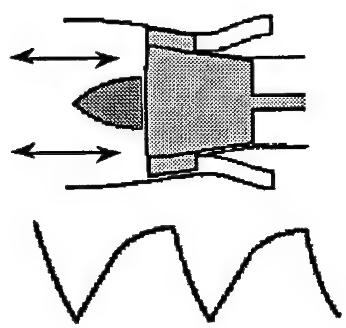


Rotating Stall

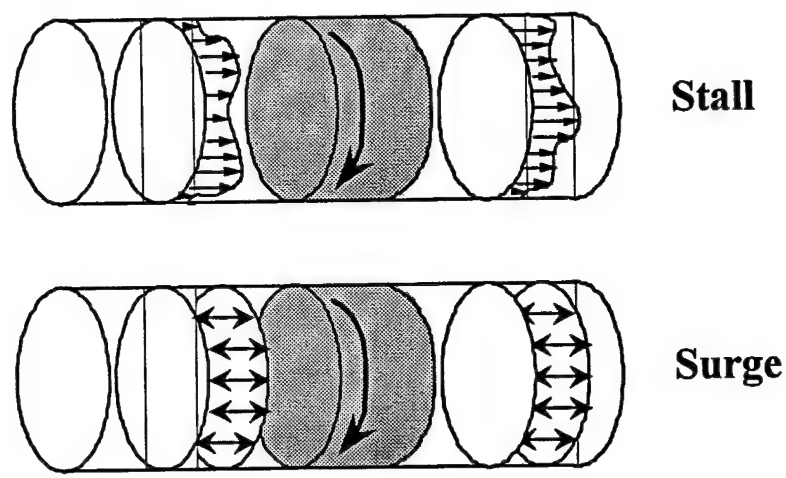


Approx. 0.5E Frequency

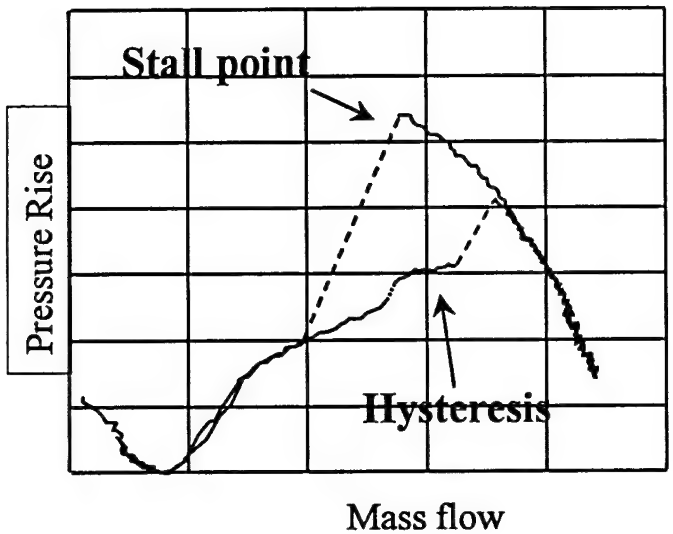
Surge

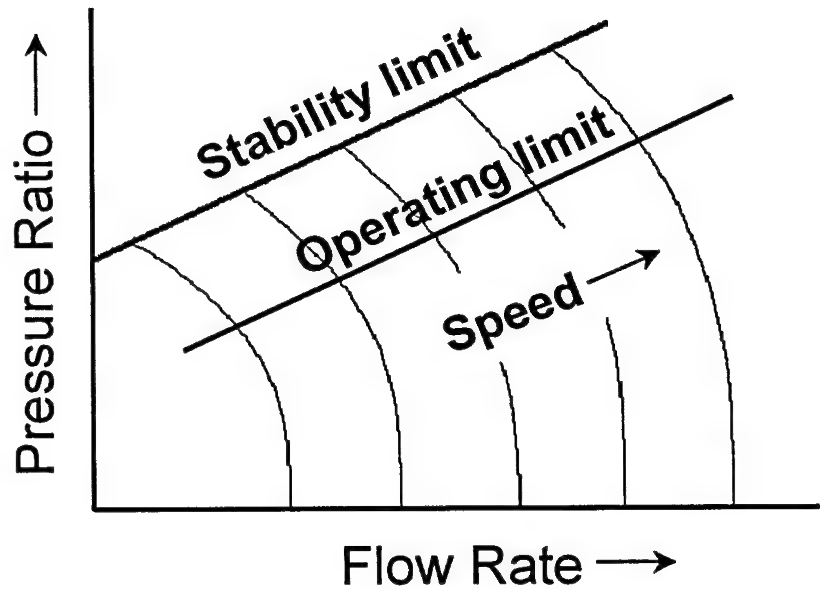


Approx. 0.3E Frequency



Impact of Stall and Surge on Engine Performance

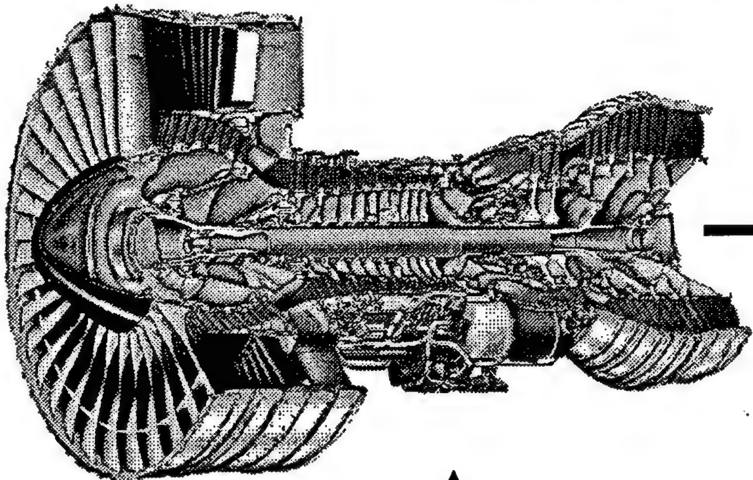


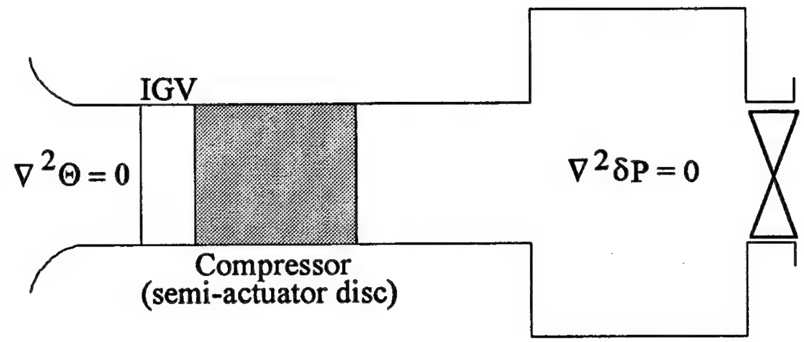


System performance limited by instability
- Number of rotors/stators required to deliver pressure set by instability limit
- Hysteresis loop forces operation away from peak pressure rise

Benefits of active control of stall/surge
- 10% decrease in stalling mass flow can lead to 2% increase in fuel efficiency (!)
- Requires system redesign, not retrofit
- Complexity, weight, reliability are important (mostly unaddressed) issues

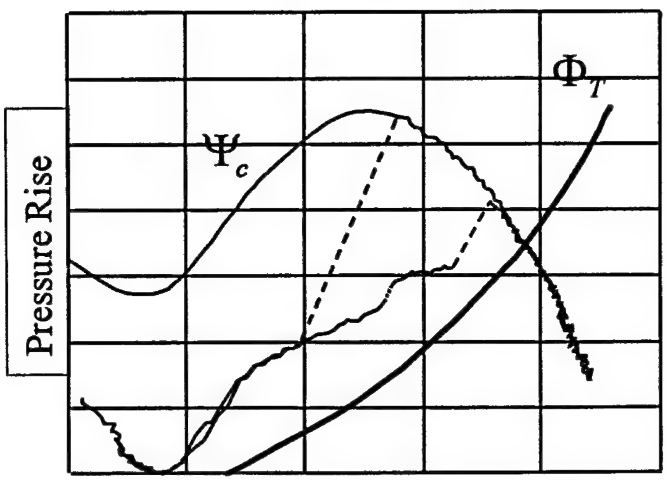
Moore-Greitzer Model (1986)





$$\Psi = \Psi_c(\Phi + \delta\phi) - l_c \frac{d\Phi}{d\xi} - \lambda \frac{\partial \delta\phi}{\partial \theta} - (\mu + m)\frac{\partial \delta\phi}{\partial \xi}$$

One mode expansion
+ Galerkin projection

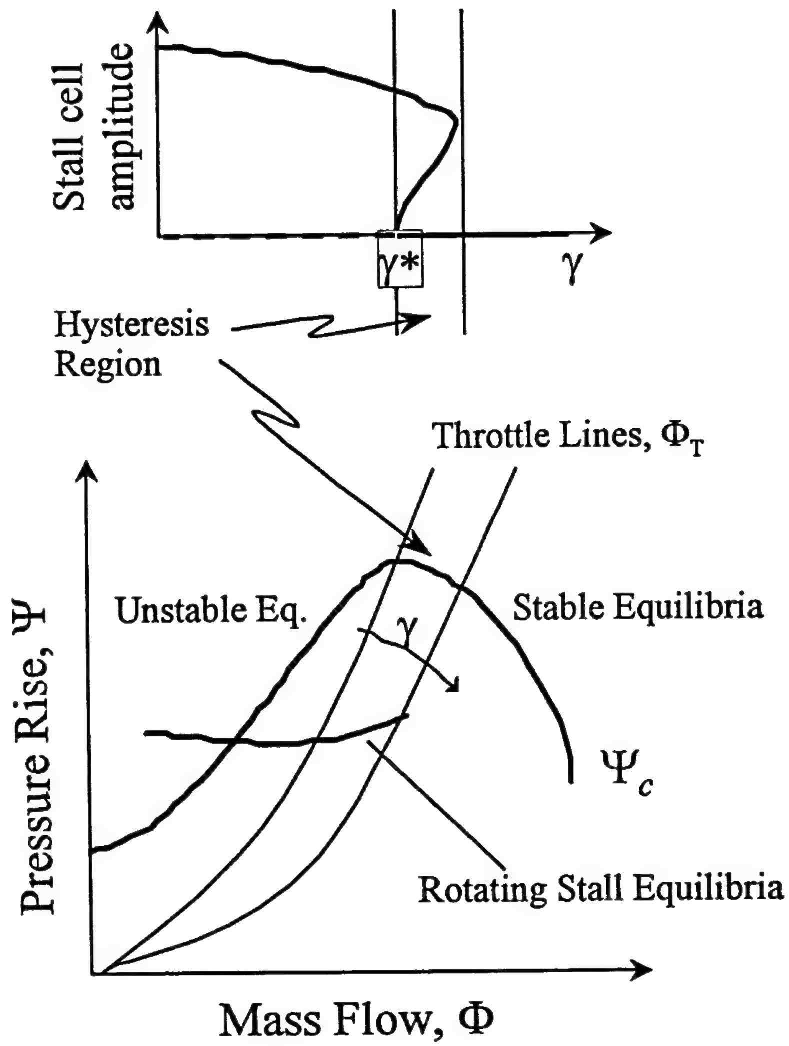


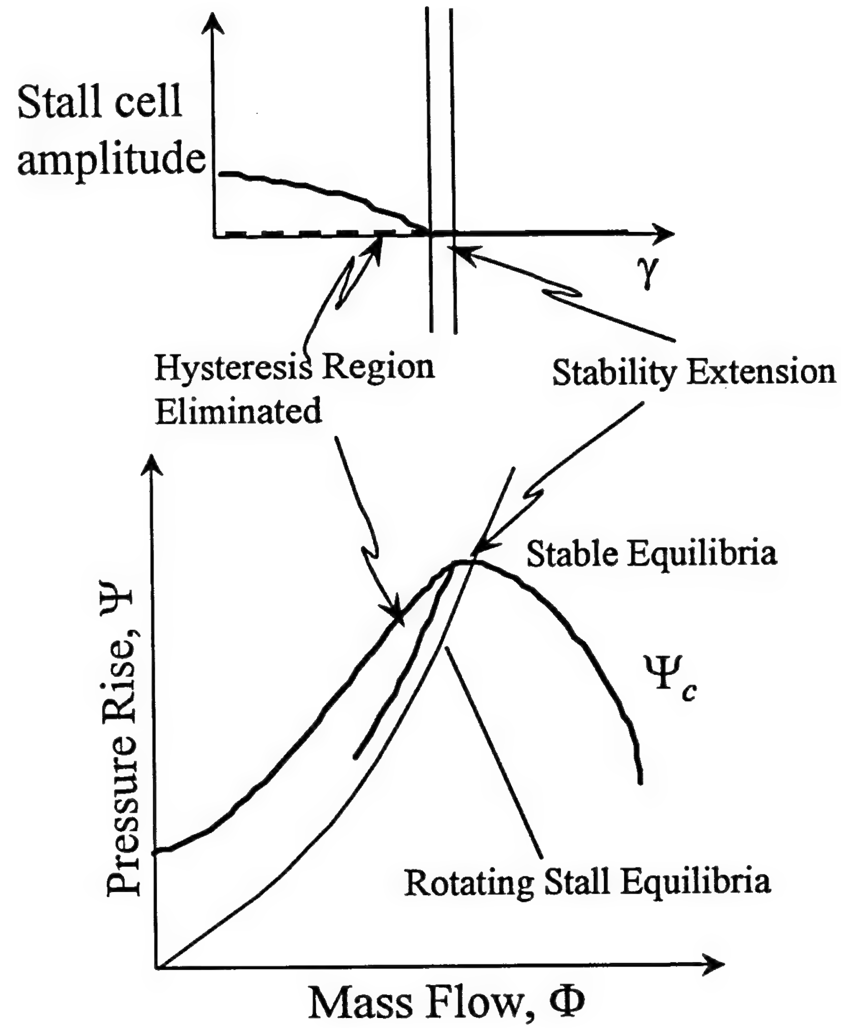
$$\dot{\psi} = \frac{1}{4B^2 l_c}(\phi - \Phi_T(\psi))$$

$$\dot{\phi} = \frac{1}{l_c}\left(\Psi_c(\phi) - \psi + \frac{J}{8}\frac{\partial^2 \Psi_c}{\partial \phi^2}\right)$$

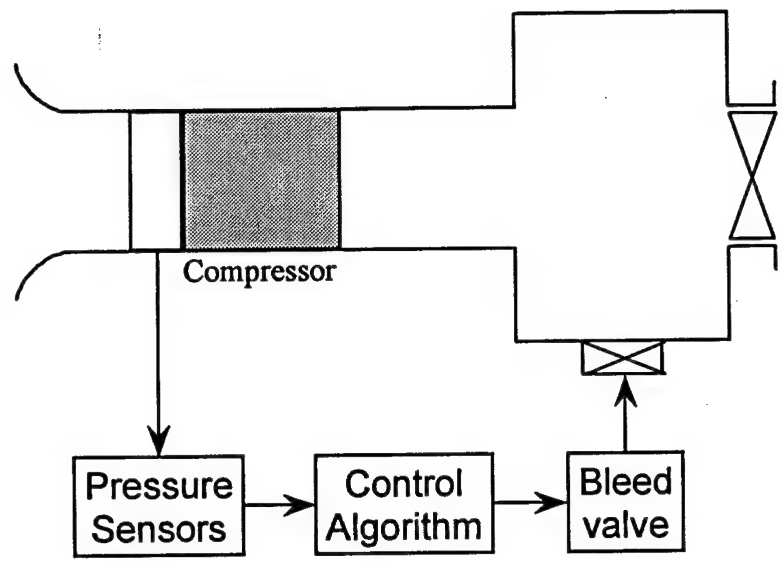
$$\dot{J} = \frac{2}{\mu + m}\left(\frac{\partial \Psi_c}{\partial \phi} + \frac{J}{8}\frac{\partial^3 \Psi_c}{\partial \phi^3}\right)J$$

Active Control Concepts: Stabilization + Bifurcation Control

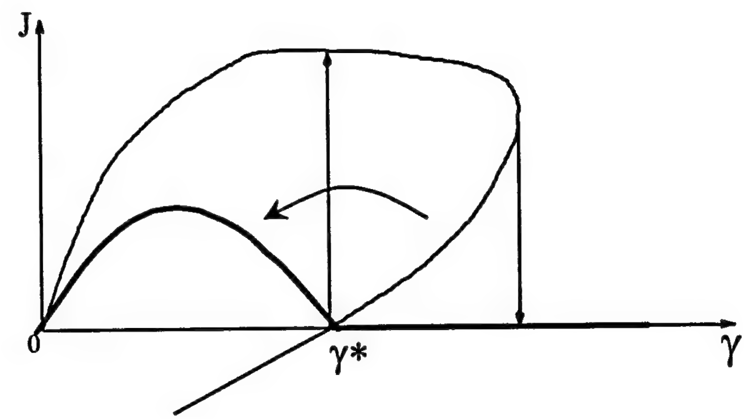




Bifurcation Control Using 1D Bleed Valves



$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - (\gamma + \underline{\underline{KJ}})\sqrt{\psi}\right)$$



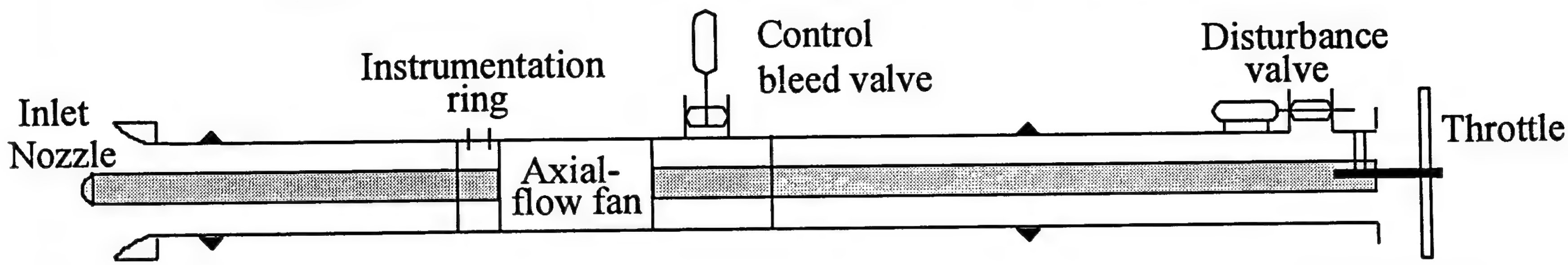
(Liaw and Abed, 1992)

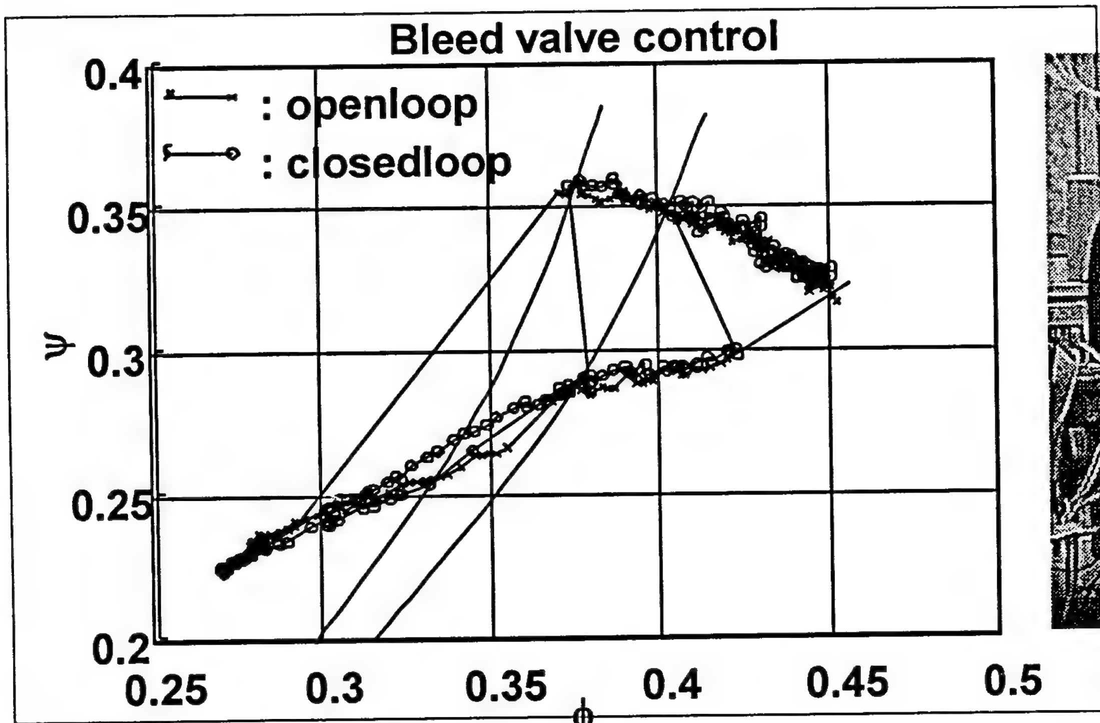
$$\boxed{K_{\min} = -\frac{\phi^* \Psi_c'''(\phi^*)}{8\gamma^* \psi^* \Psi_c''(\phi^*)} - \frac{\gamma^* \Psi_c''(\phi^*)}{8\psi^*}}$$

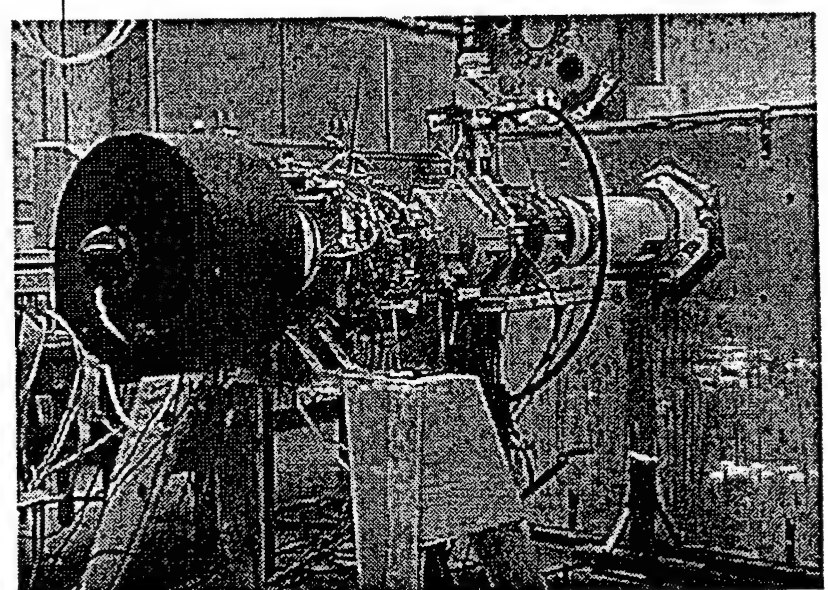
Remarks:

- Can show system is not stabilizable $\Rightarrow$ can only achieve operability enhancement
- Achieve performance benefit by engine redesign; operate closer to peak pressure
- 2D actuation (IGV, BV, or AI) gives stability extension, but more complex (?)

Implementation on Caltech Compressor Rig

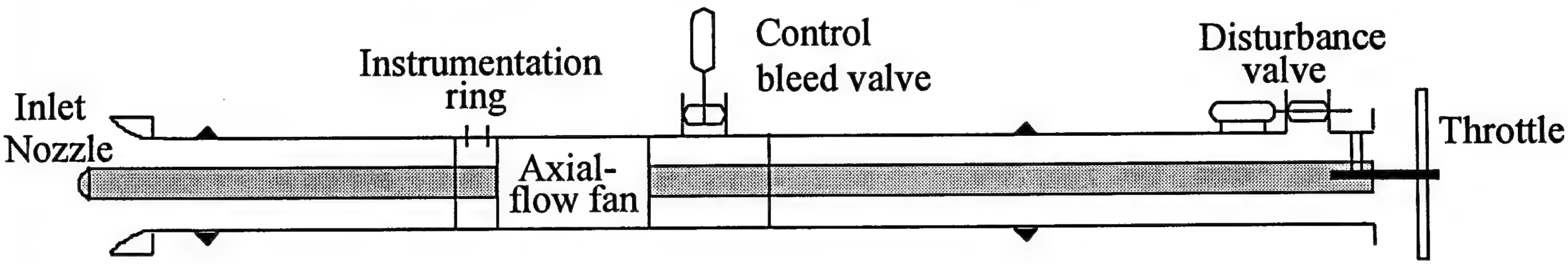


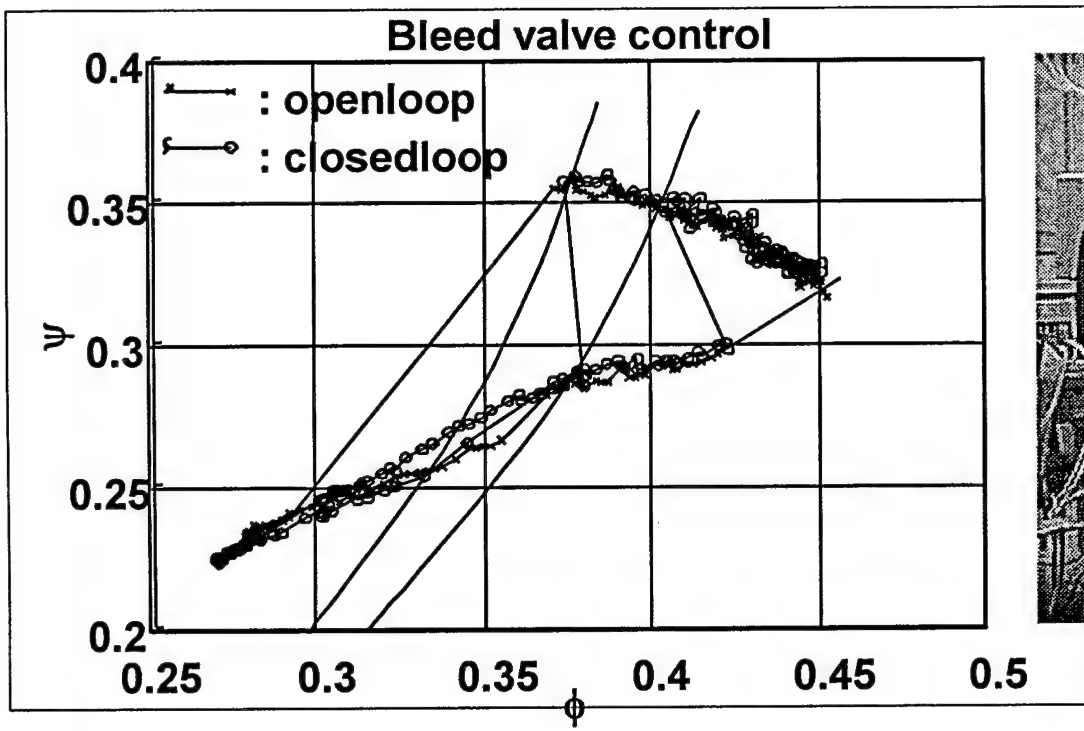


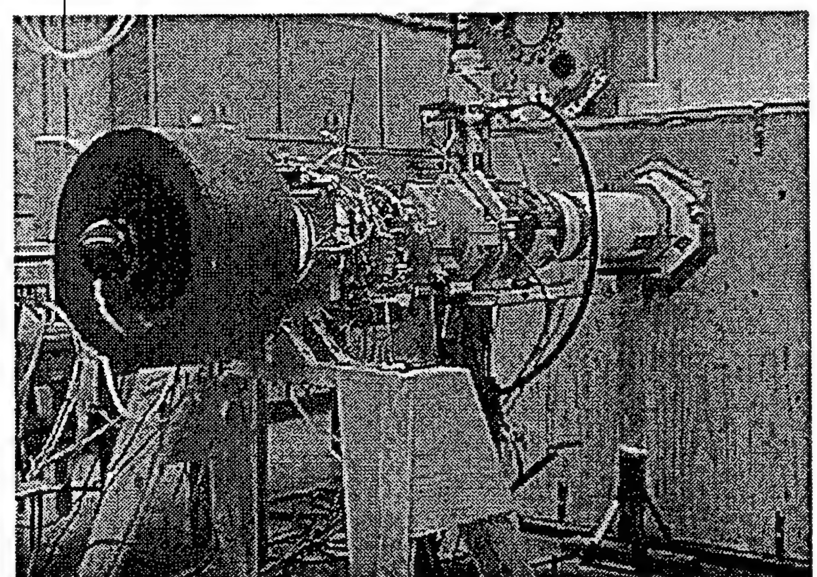


Yeung & Murray, JPC 97

Implementation on Caltech Compressor Rig

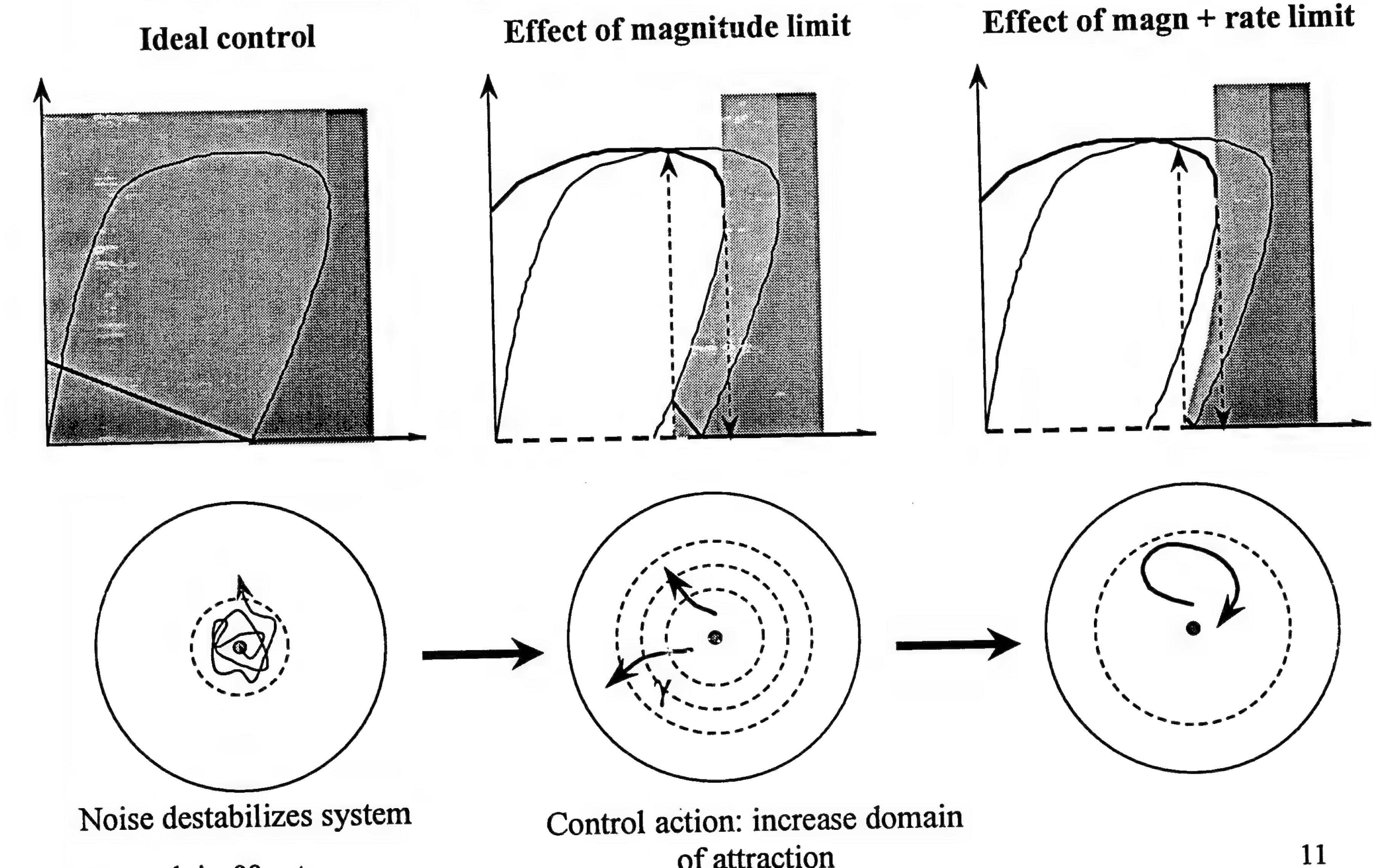






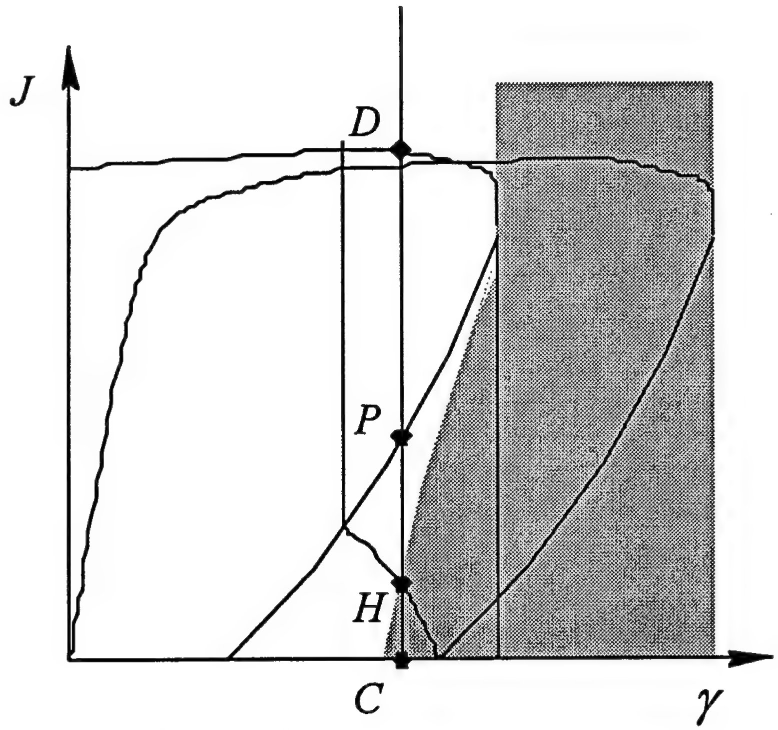
Yeung & Murray, JPC 97

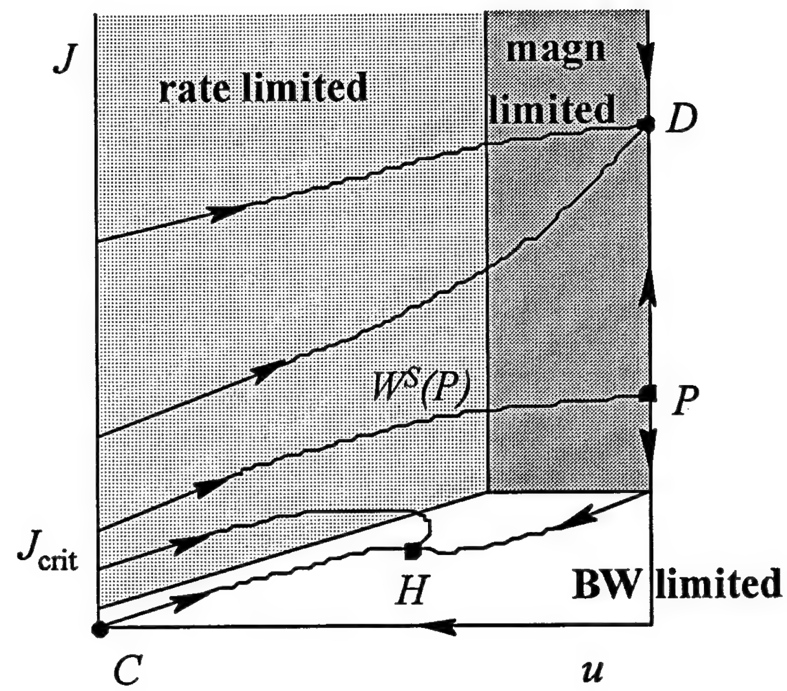
Bifurcation Control w/ Magnitude and Rate Limits



gatech-jun98.ppt
Wang & Murray, CDC 97

Analysis of Effects of Magnitude and Rate Saturations





Approximate MG3 model using center manifold near bifurcation point

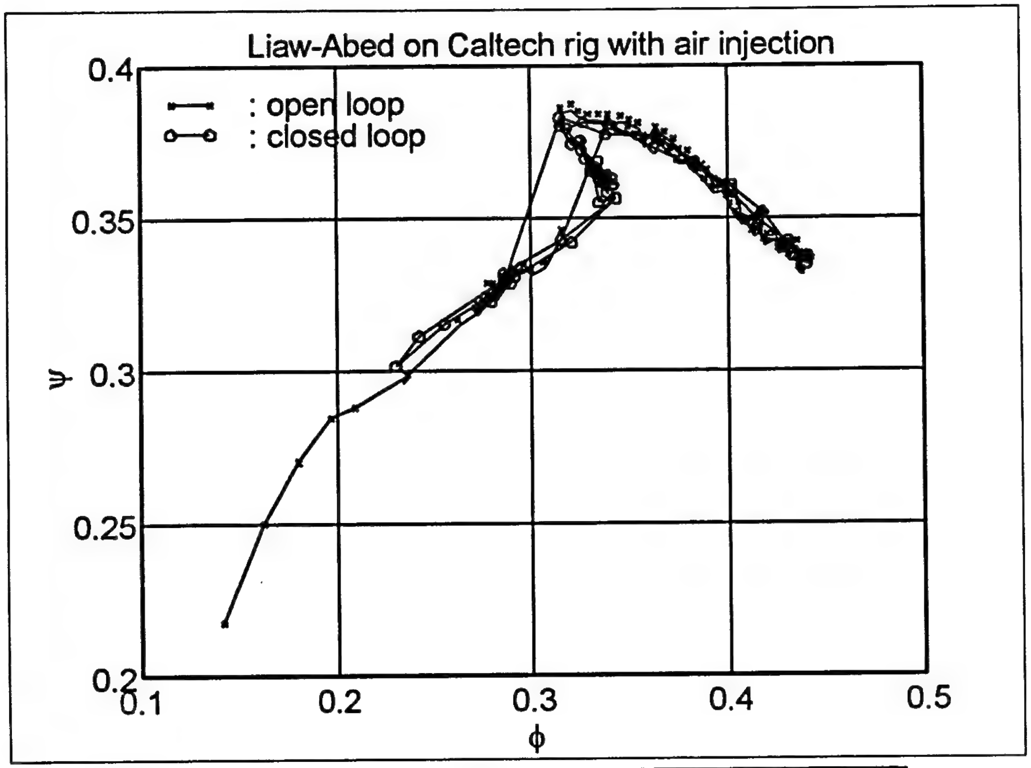
$$\frac{dJ}{d\xi} = \alpha_1(\gamma - \gamma_0 + u)J + \alpha_2 J^2 + \mathcal{O}(\delta J^2, J^3), \qquad \alpha_1 = \frac{2\sqrt{\Psi_0}\psi_c''}{m+\mu}, \quad \alpha_2 = \frac{1}{4(m+\mu)}\left(\psi_c''' + \frac{\gamma_0 \psi_c''^2}{\sqrt{\Psi_0}}\right)$$

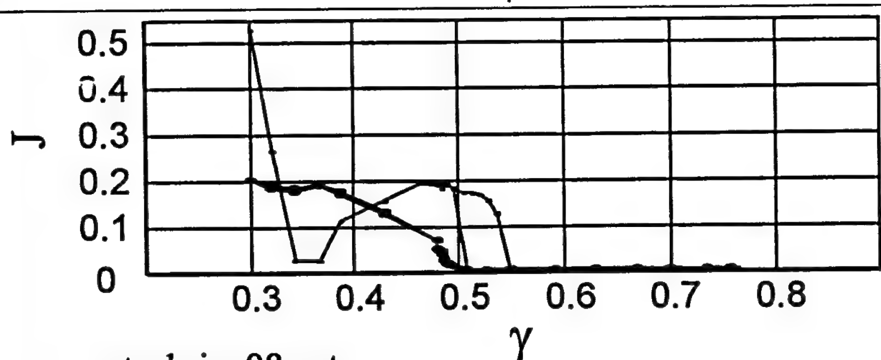
Compute operability enhancement using piecewise linear approximations

$$\Delta = u_{mag} \frac{1 - \frac{2}{\pi}\arctan\left(\frac{\pi}{4}\sigma\eta\right)}{1 - \frac{\sigma}{1+\sigma}\frac{2}{\pi}\arctan\left(\frac{\pi}{4}\sigma\eta\right)} \qquad \sigma = \frac{-\alpha_1 u_{mag}}{\alpha_2 \epsilon}, \quad \eta = \frac{\alpha_2 \epsilon u_{mag}}{u_{rate}},$$

Wang & Murray, CDC 97

Experimental Results Using Modified Ψ_c





Use steady air injection to shift Ψ_c

- Changes shape of Ψ_c to give lower rate requirements
- Implication: actuator requirements strongly affected by system design

Other shifting mechanisms possible

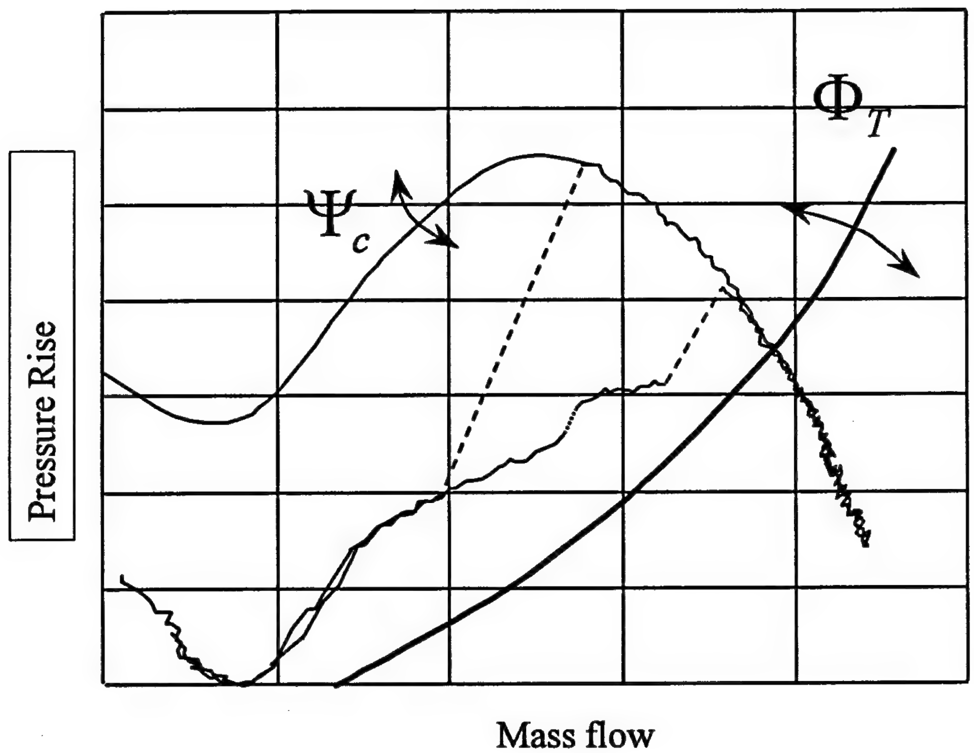
- Blade redesign
- Casing treatments

Lesson Learned:

Must consider controllability in the design process

Yeung & Murray, JPC 97

Control of Rotating Stall Using Air Injection

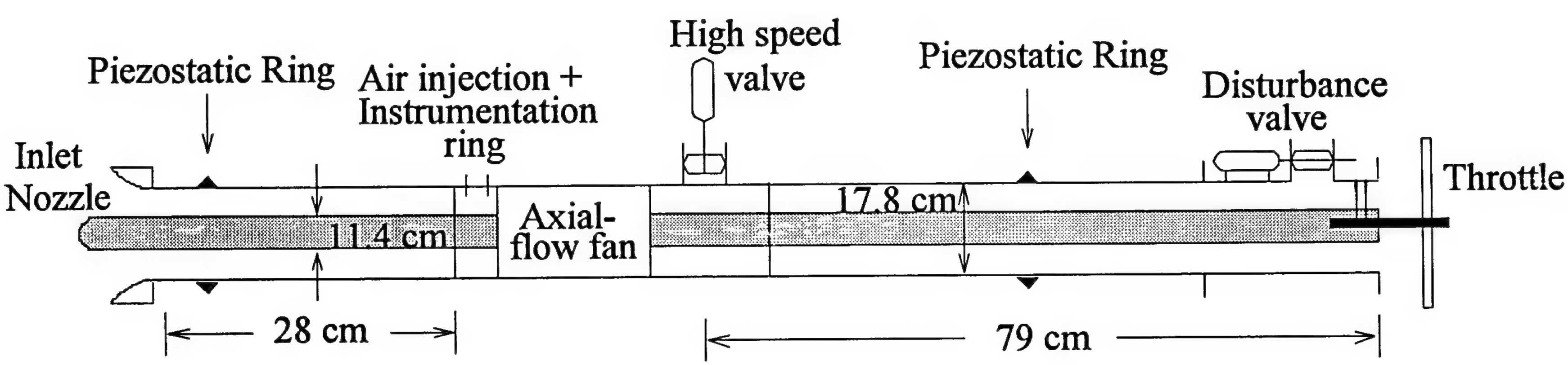


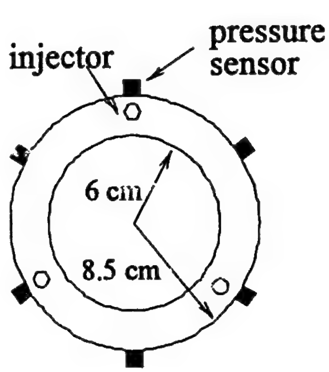
Use air injection (AI) to modulate compressor characteristic

- Air injectors modify local angle of attack $\Rightarrow$ affect Ψ_c
- MG3 model indicates operability enhancement should be possible

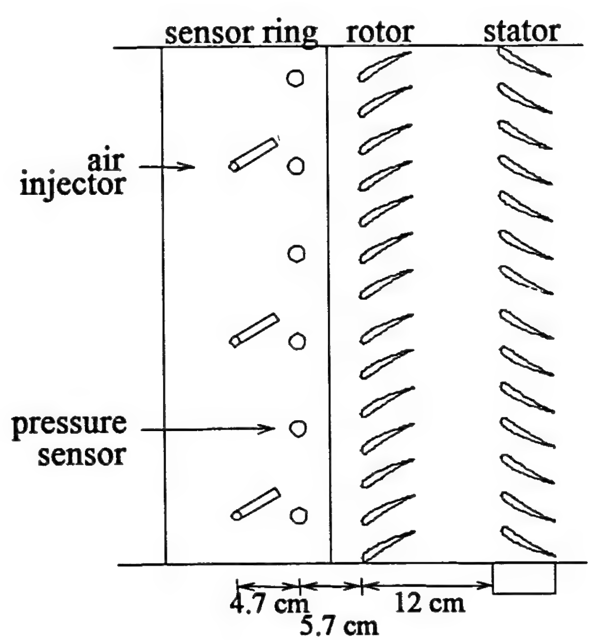
$$\Psi_c = \Psi_{c,\mathrm{nom}} + \Psi_{c,\mathrm{ai}} u$$

Caltech Low Speed, Axial Flow Compressor Experiment





sensor ring (end view)

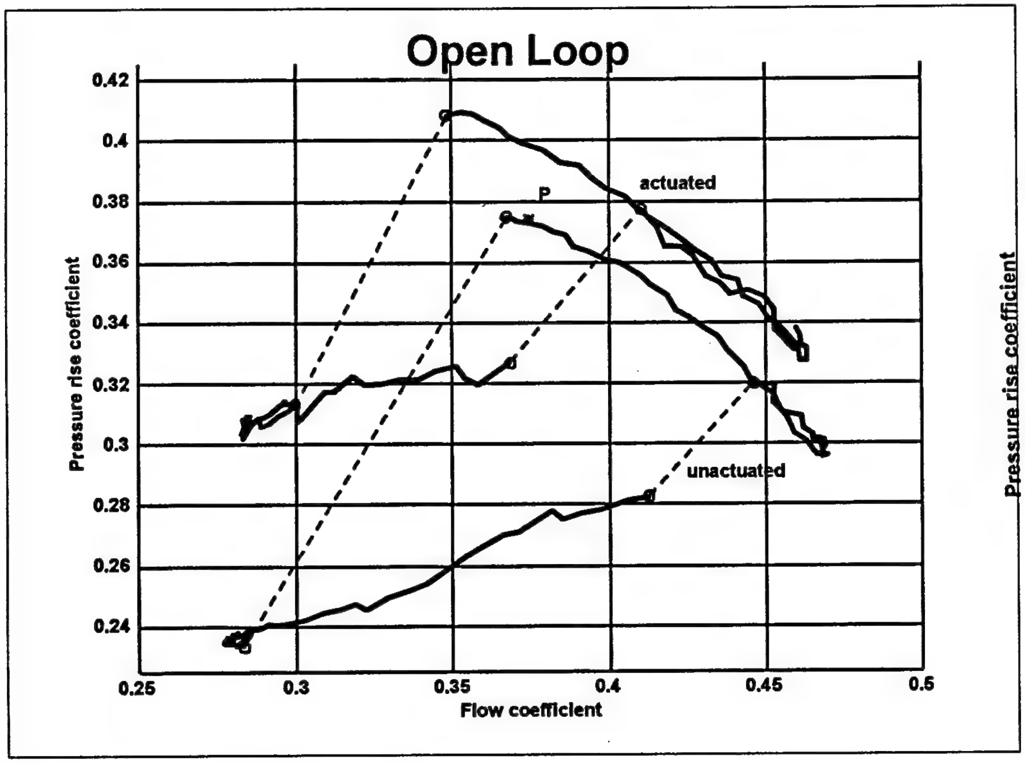


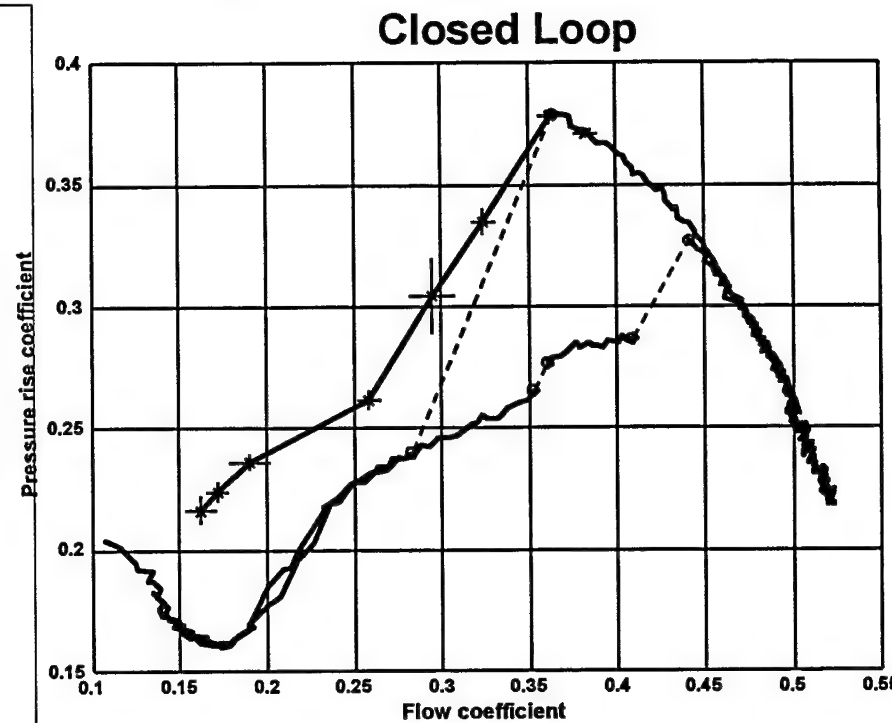
sensor ring (side view)

Rig parameters

- Operating point: 6,000 rpm (100 Hz)
- Stall frequency: 3925 rpm (65.4 Hz)
- Jet flow: 0.1% to 1% of mean flow
- On/off actuators, approx 200 Hz BW

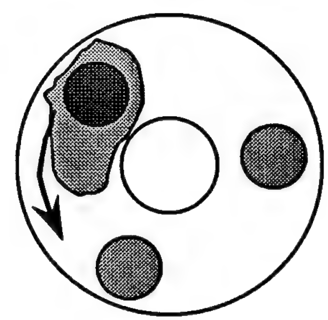
Experimental Results



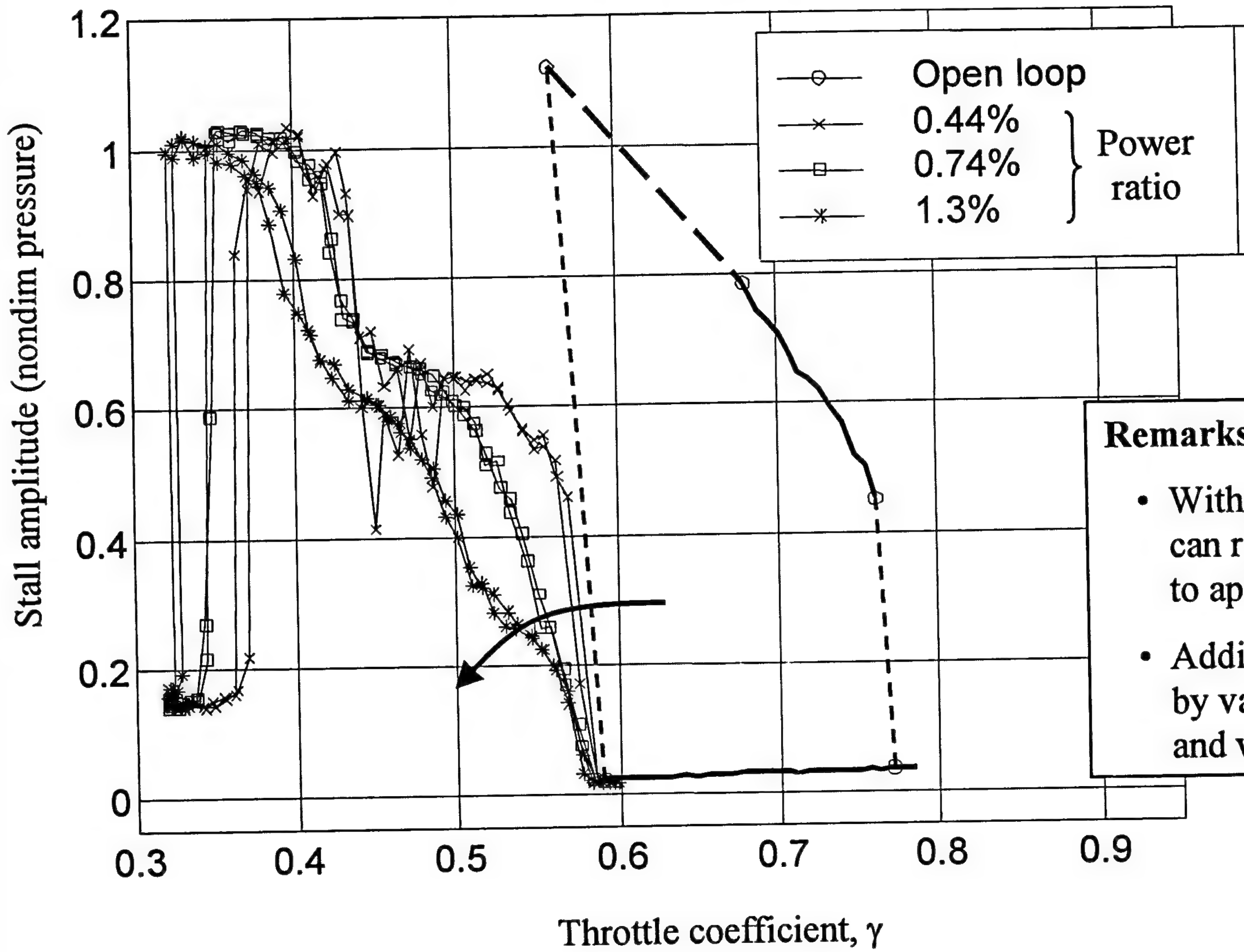


Control algorithm:

- Detect magnitude, phase of stall cell
- Turn on injector when cell is in window
- Leave injector on for fixed time



Actuator Authority Tradeoff

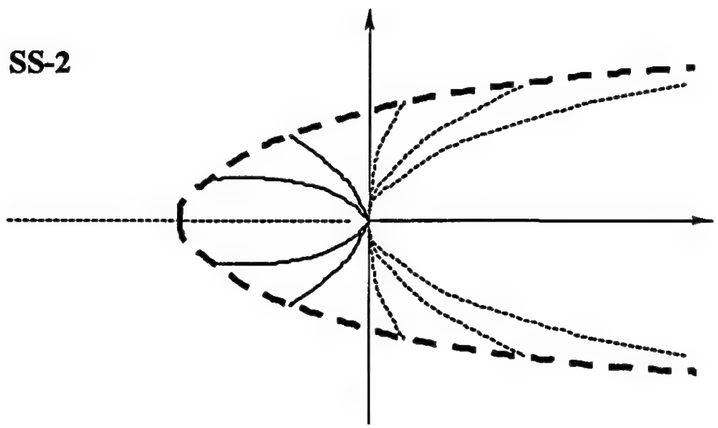


Remarks:

- With optimization, can reduce power flux to approx 0.15%
- Additional tradeoffs by varying number and width of injectors

Bifurcation Control in the Presence of Magnitude Limits

SS-2

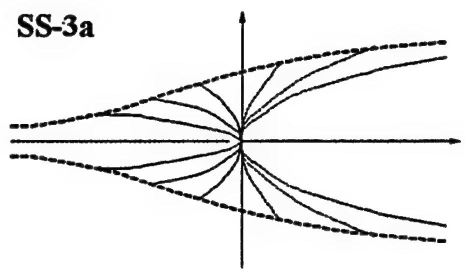


Analytical study of effects of magn limits

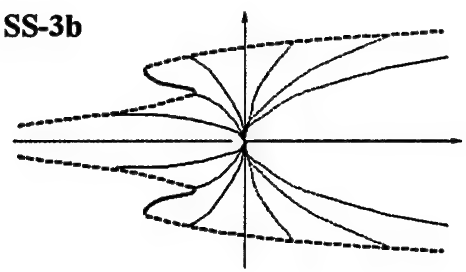
- Rely on normal forms around center mfd
- Different actuation mechanisms possible
- Gives qualitative information, insight
- SS-2: magn constraints don't limit operability
- SS-5: can't make equil pt arbitrarily small

Next: add rate limit effects

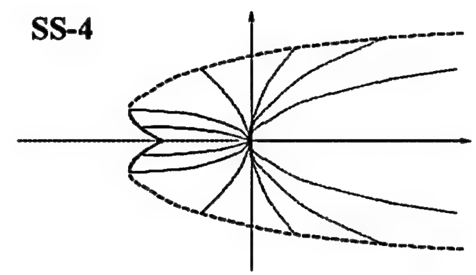
SS-3a



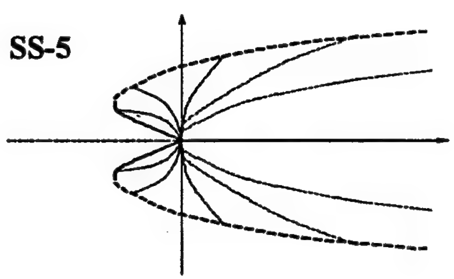
SS-3b



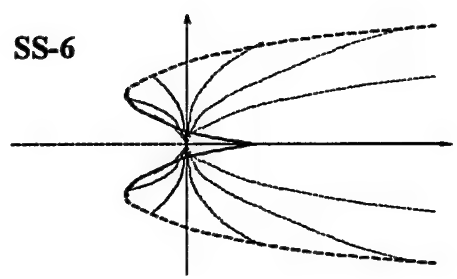
SS-4



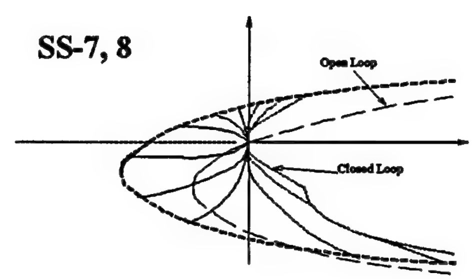
SS-5



SS-6



SS-7, 8



Summary and Conclusions

Operability enhancement using bleed valves is severely limited by actuator magnitude and rate constraints

- Shape of compressor characteristic has strong effect on rate requirements
- Control configured design required: take into account *unstable* characteristic
- 2D BV results may have significantly better results (in progress at MIT)

Pulsed air injection results look encouraging

- Low speed tests show good operability enhancement with large range
- High speed tests schedule for transonic rig at NASA Lewis (w/ MIT)
- Power requirements are still large; tradeoff study in progress (BM, UM, UP)
- Secondary effects not yet considered: unsteady response on blades $\Rightarrow$ HCF?

Basic theory for bifurcation control in presence of actuator constraints is under development

- Magnitude constraints: actuation mechanism has strong effect on results
- Current analysis relies on MG3 + center mfds $\Rightarrow$ may be very local
- Working on extension to higher order systems, simultaneous rate constraints

The NASA-Lewis Compression Stability Program

Georgia Tech University Initiative on Intelligent Turbine Engines

June 15-16, 1998

Tony Strazisar
Senior Technologist
NASA-Lewis Research Center

Stage loading trends, modern multistage compressors

PWA 4098 ***(early 90's)***	PWA 8000 ***(first engine, 3/99)***
Eleven stages	5 stages
10:1 pressure ratio	12:1 pressure ratio

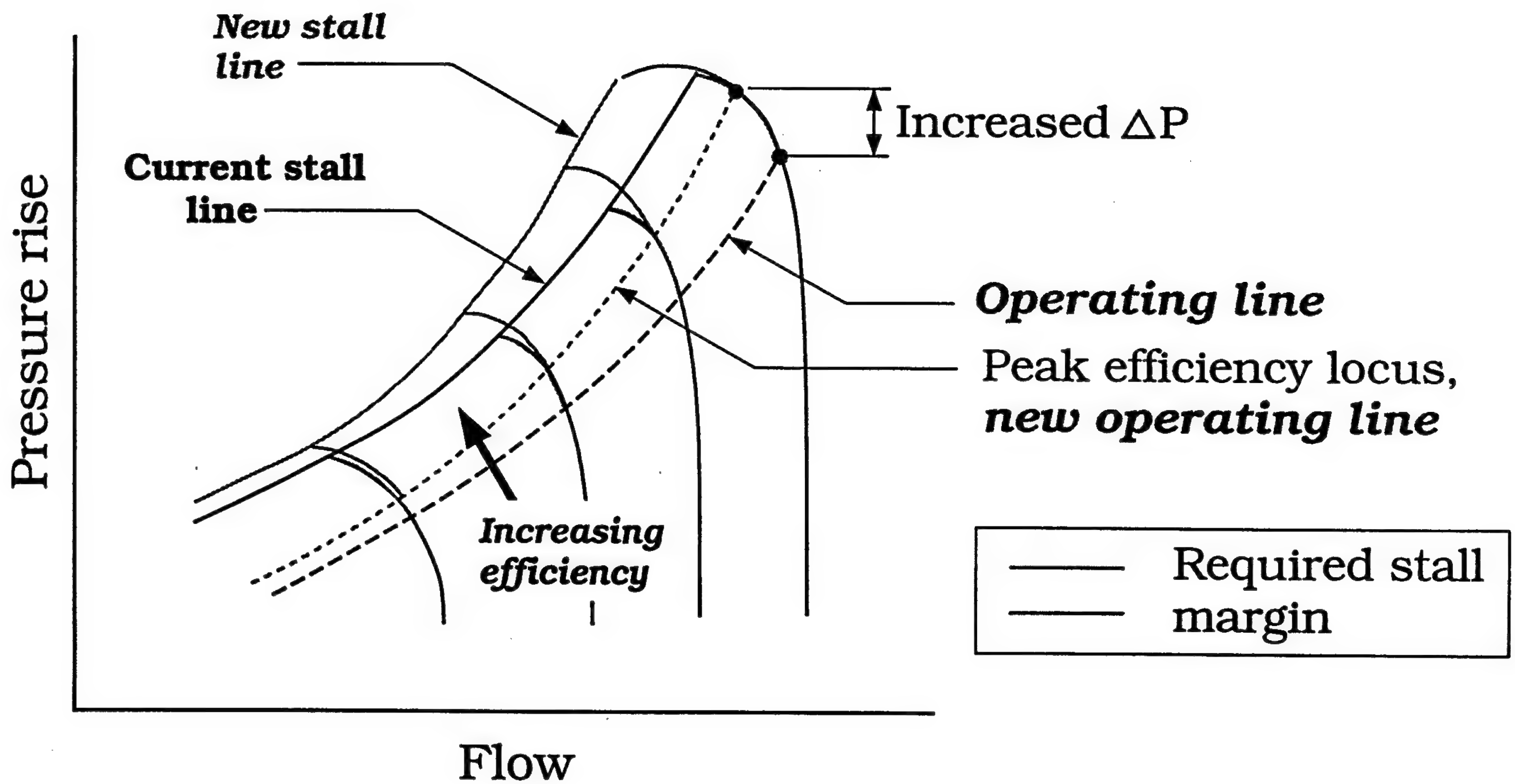
Aviation Week, 2/23/98

What is the limit of stage loading which can be achieved through blade shape alone?

Strategies for increasing loading beyond this limit while maintaining operability:

- Aspirated endwalls/blade surfaces
- Jet-flapped stators (circulation control)
- Stability enhancement

Stability enhancement technology can enable increased pressure rise and efficiency with no reduction in stall margin



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Benefits

- ***Improved aero performance:***

  5-10% increase in stall margin provides:

  Small turbofan engine:

  5% increase in core compressor PR for an existing machine
  1% decrease in SFC for an existing machine

  3.5% increase in engine SFC for a new, optimized design
  5% decrease in fan speed
  10% decrease in fan system weight

  Large turbofan engine:

  - 1.5% increase in core compressor efficiency

  Military (IHPTET):

  - Attainment of loading goals

- ***Improved operability (wider safe operating range)***

- ***Improved tolerance to performance deterioration***

Fan & Compressor Stability Enhancement

Task Description:

Develop and demonstrate new methodologies for enabling management of stall in axial compressors.

Approach:

- **Off-Design flow prediction system - assess static stability**
  CFD codes for steady-state performance prediction (APNASA) - provide ***a priori compressor characteristics*** for stability models

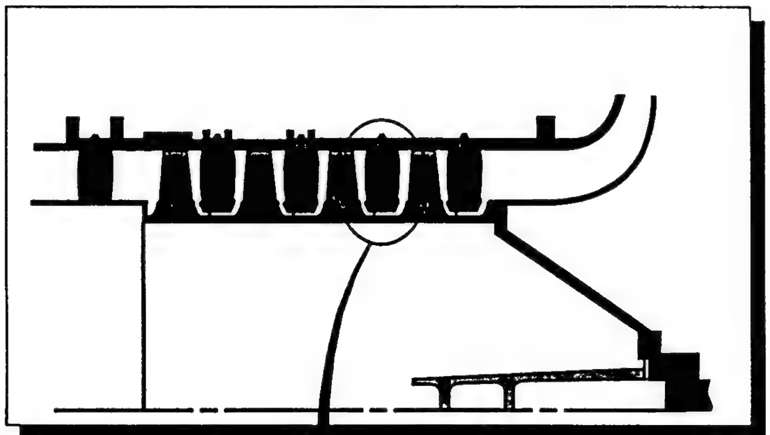
- **Stability modelling system - assess dynamic stablity**
  Predict ***instability mode*** (short or long wavelength) and ***least stable stage*** in a multistage compressor

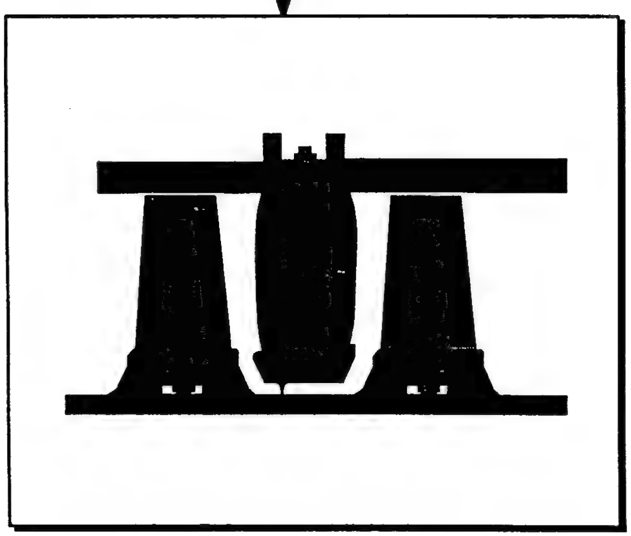
- **Stability enhancement through injection**
  - ***Steady*** injection, ***casing treatment***
  - Linear and non-linear ***active control*** of injection

- **Stability enhancement with magnetic bearings**
  - ***Shaft centering*** via magnetic bearings
  - ***Active*** tip clearance (via magnetic bearing)

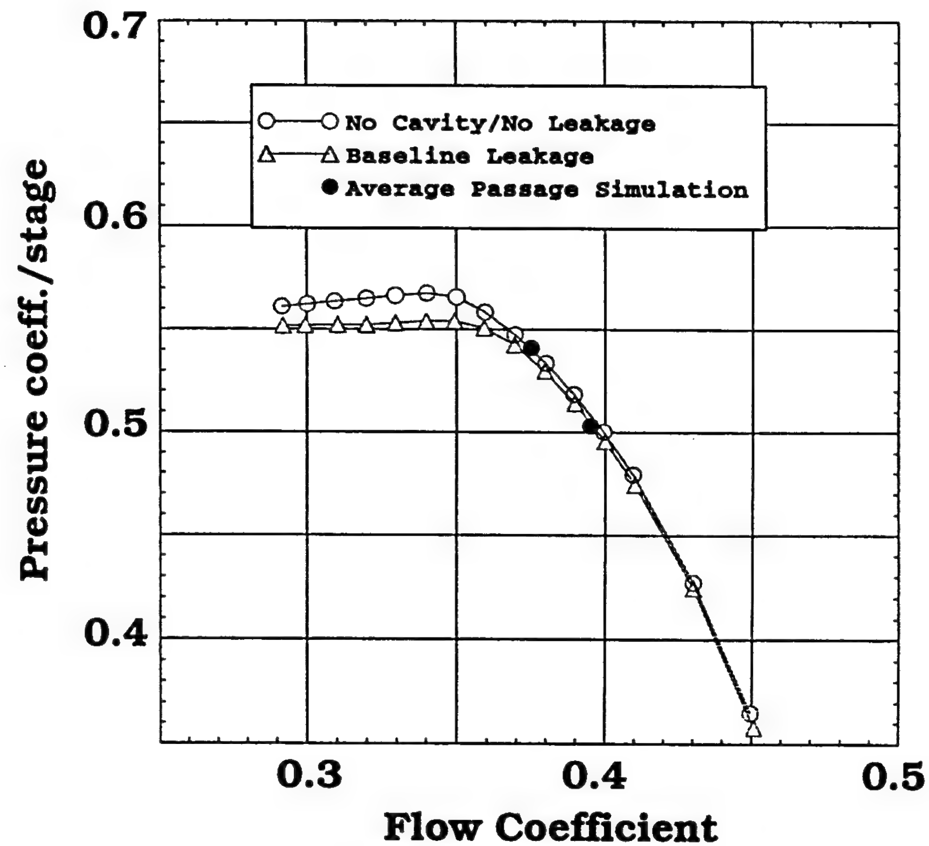
Performance Impact of Stator Hub Leakage

NASA-Lewis Low Speed Axial Compressor





Hub-shrouded stator cavity



Modelling of 3D Aerodynamic Instabilities in Multistage Compressors

Yifang Gong/Choon Tan, MIT

Simulated development of short-wavelength disturbance

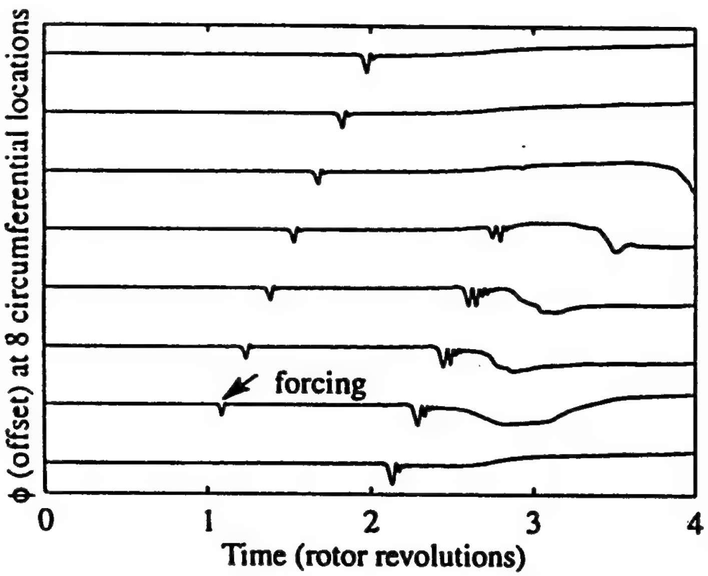


Figure 5: Computed flow coefficient traces at the tip of the first rotor inlet for a compressor stalling via short wavelength route.

Measured development of short-wavelegth disturbance, GE low speed 4-stage compressor

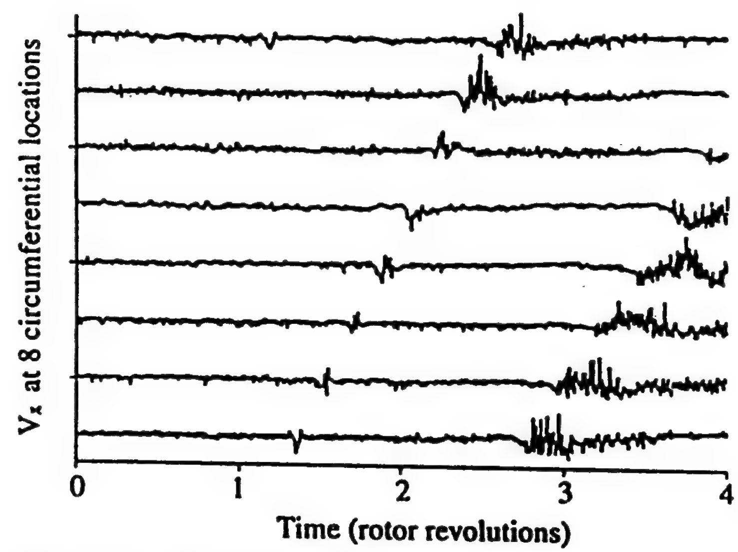


Figure 8: Measured axial velocity traces at the tip of the first rotor inlet during stall inception (Silkowski, 1995).

Modelling of 3D Aerodynamic Instabilities in Multistage Compressors

Parametric assessment of dynamic stability, GE low-speed 4-stage compressor

Different instability mode for 1st and 3rd stage

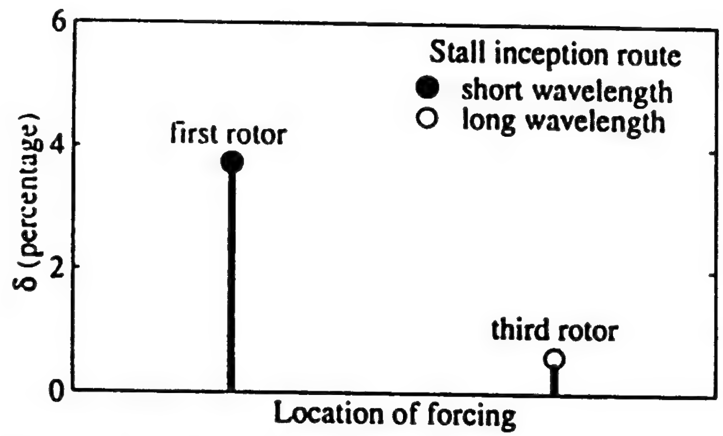


Figure 17: Changes in stall point and inception type with location of initial spike.

Stability dependent on rotor/stator axial gap

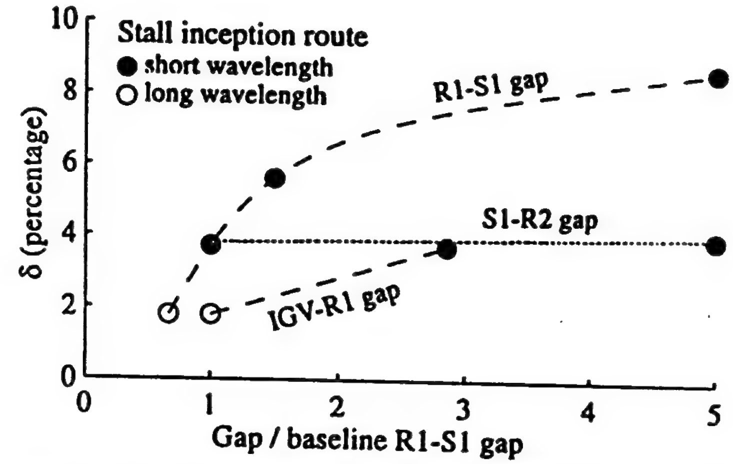
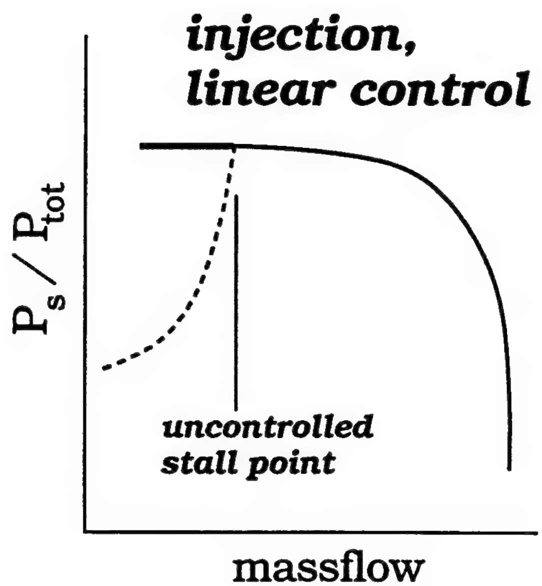


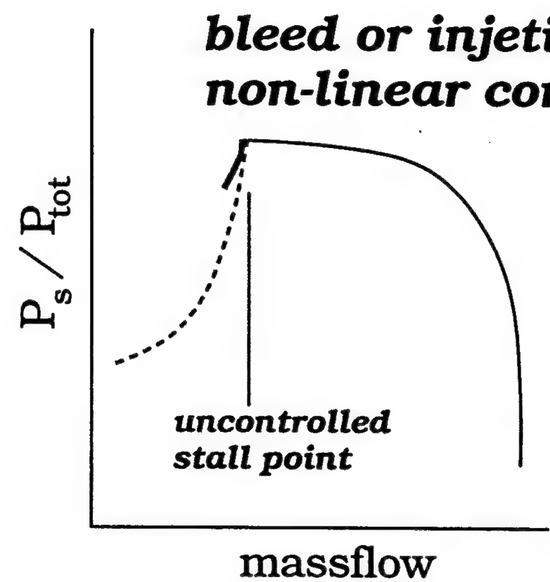
Figure 18: Effects of IGV-R1, R1-S1, and S1-R2 gap lengths on stall point and inception type.

Multistage compressor dynamic stability may be determined by "stage groups" (S-R-S) rather than by individual blade rows

Differences in Stall Control Strategy



Increased range
No drop in pressure rise
Rotating stall onset delayed



Little or no range extension
Pressure rise drops
Small amplitude rotating stall

------------	Transient, uncontrolled post-stall response
———	Controlled, steady-state conditions

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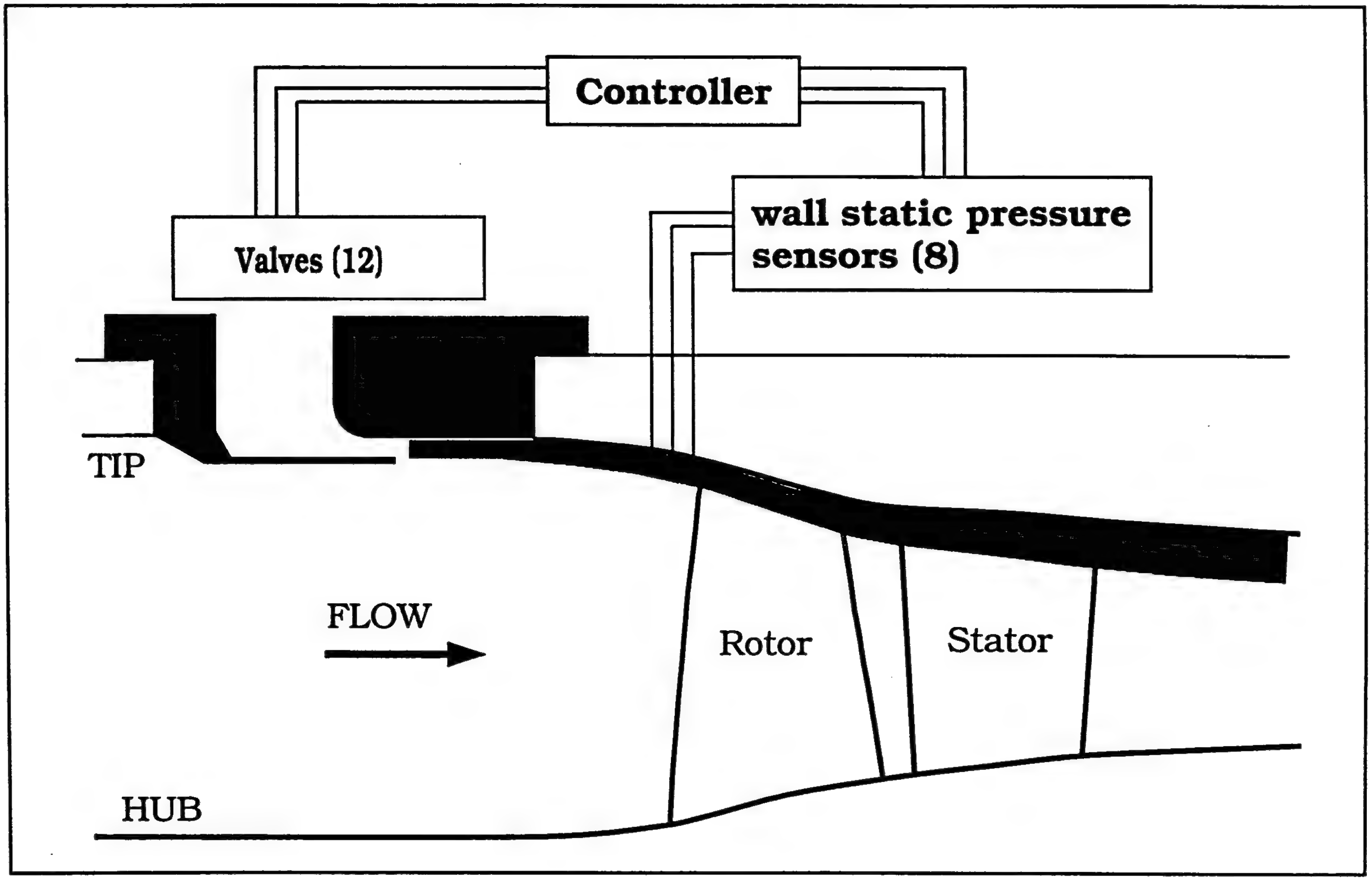
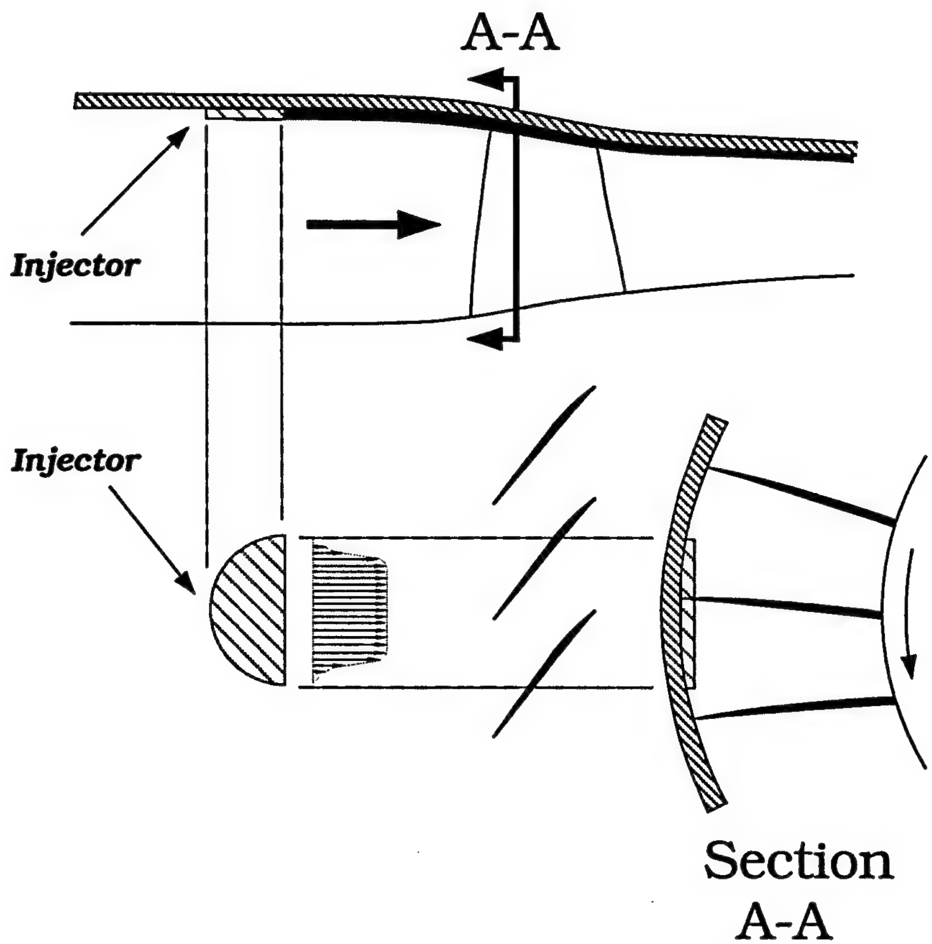
Stability Enhancement Through Tip Injection Passive & Active Control

MIT/NASA - 1996

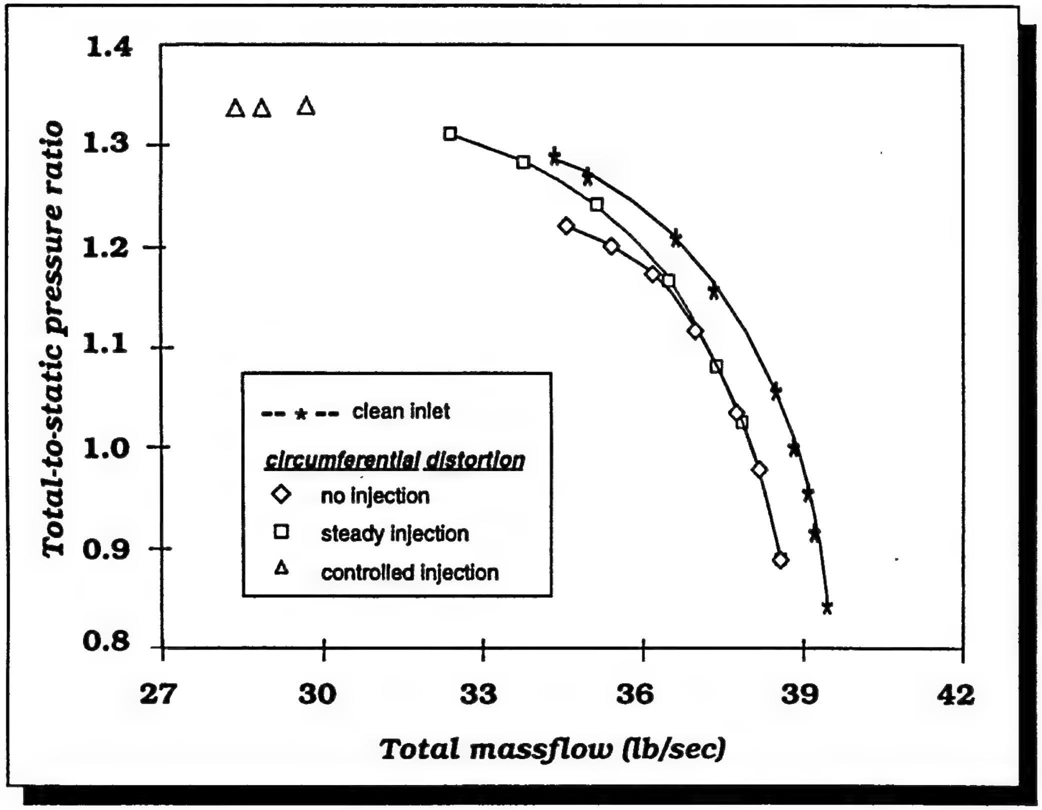


Scale drawing of sheet injector and compressor flowpath



NASA Stage 35 Stability Enhancement for Circumferential Distortion
Utip=1265 ft/sec (85% design speed)

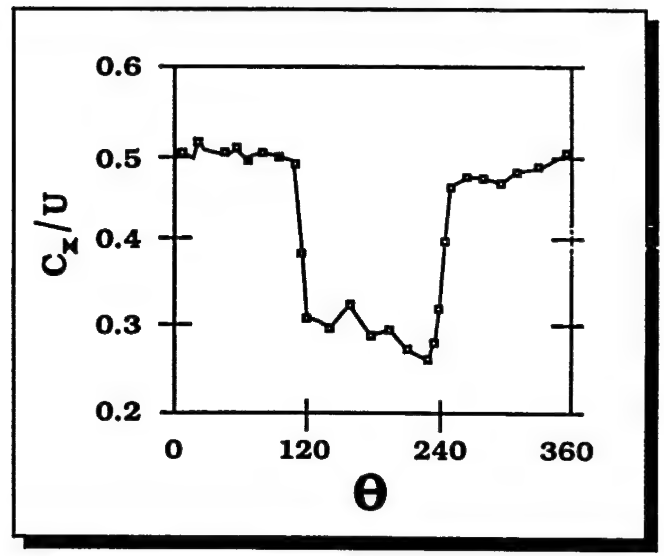
Injected flow = 4.5% of clean inlet stalling massflow



Stalling massflow reduction relative to no injection:

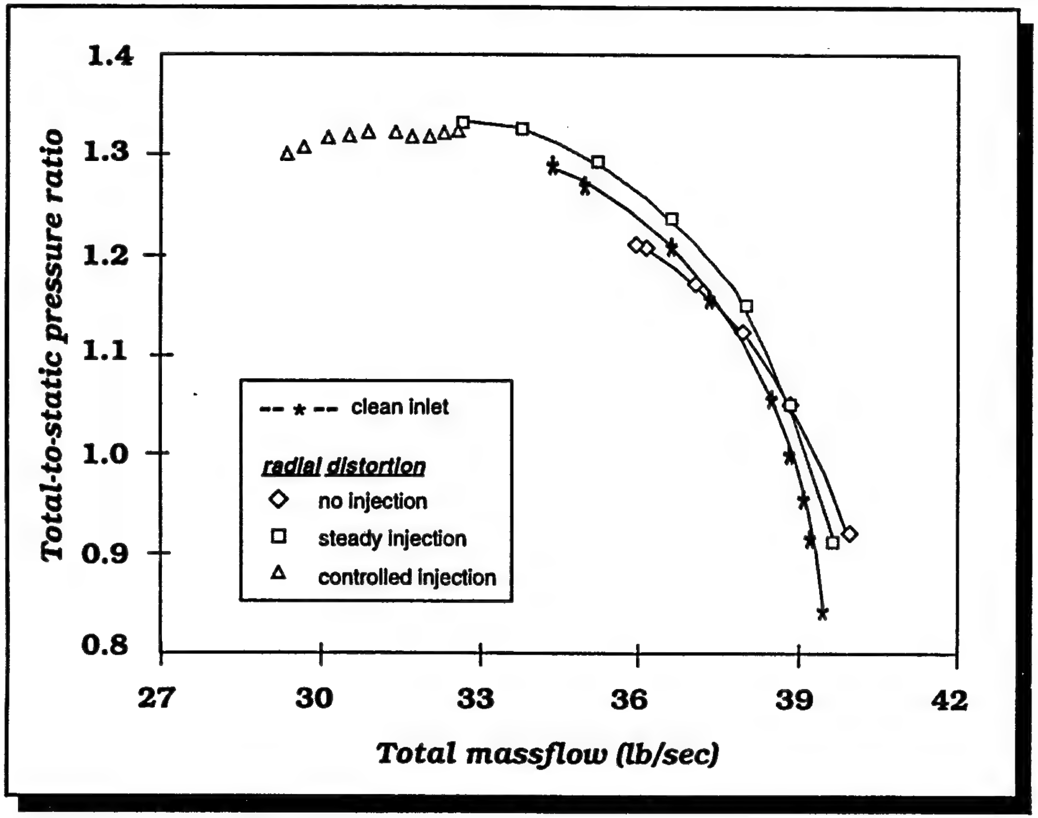
Steady injection:	6.2%
Controlled injection:	10.2%

Circumferential Distortion Profile
DC(60) = 0.61



NASA Stage 35 Stability Enhancement for Radial Distortion
Utip=1265 ft/sec (85% design speed)

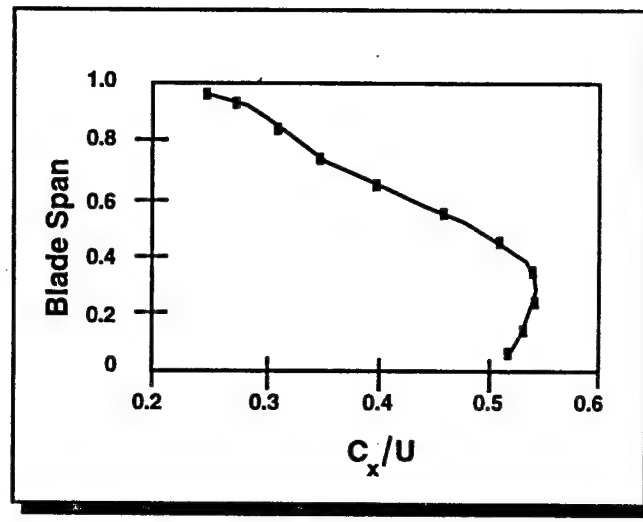
Injected flow = 4.5% of clean inlet stalling massflow



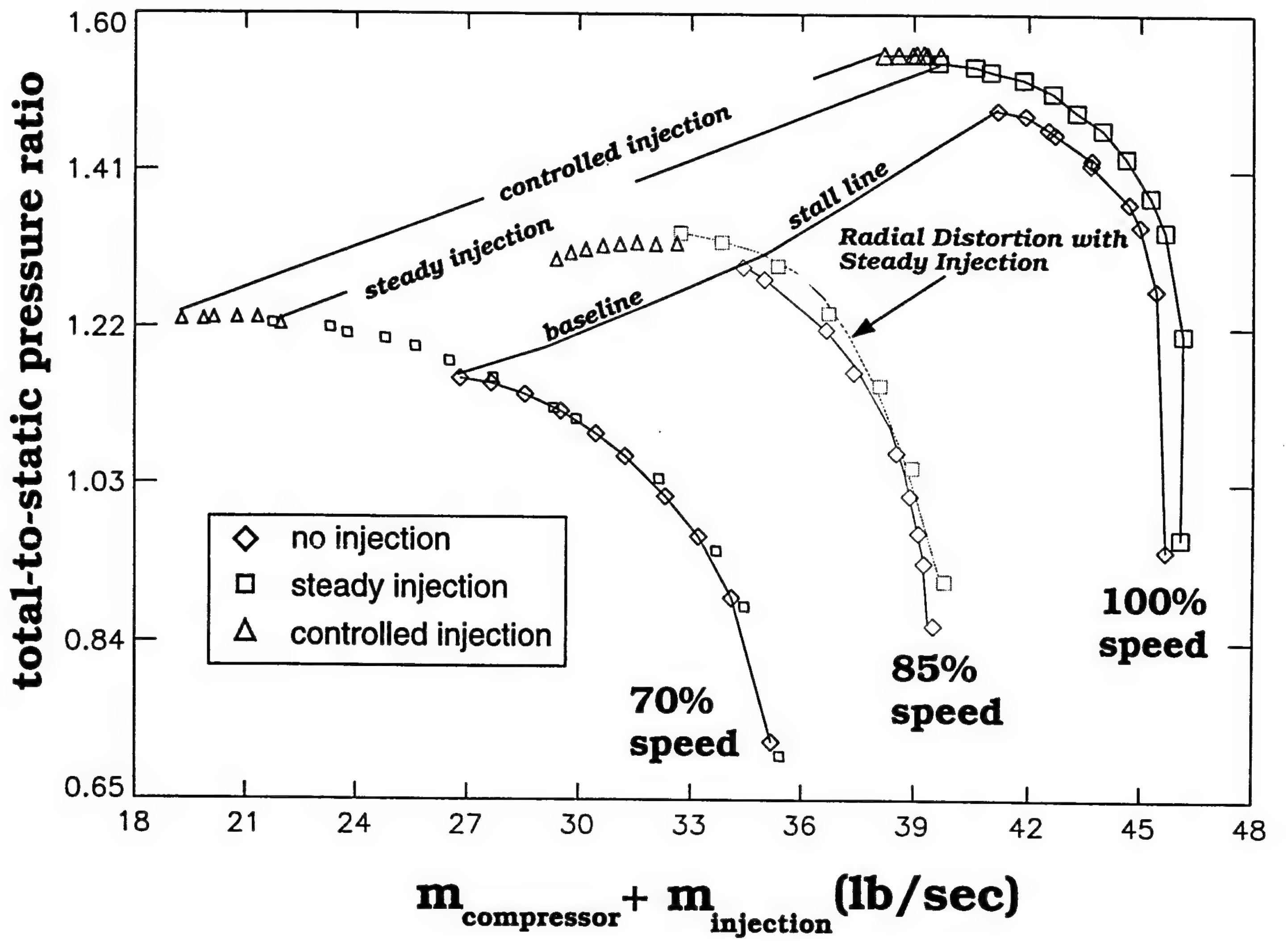
Stalling massflow reduction relative to no injection:

Steady injection: 9.7%
Controlled injection: 7.5%

Radial Distortion Profile

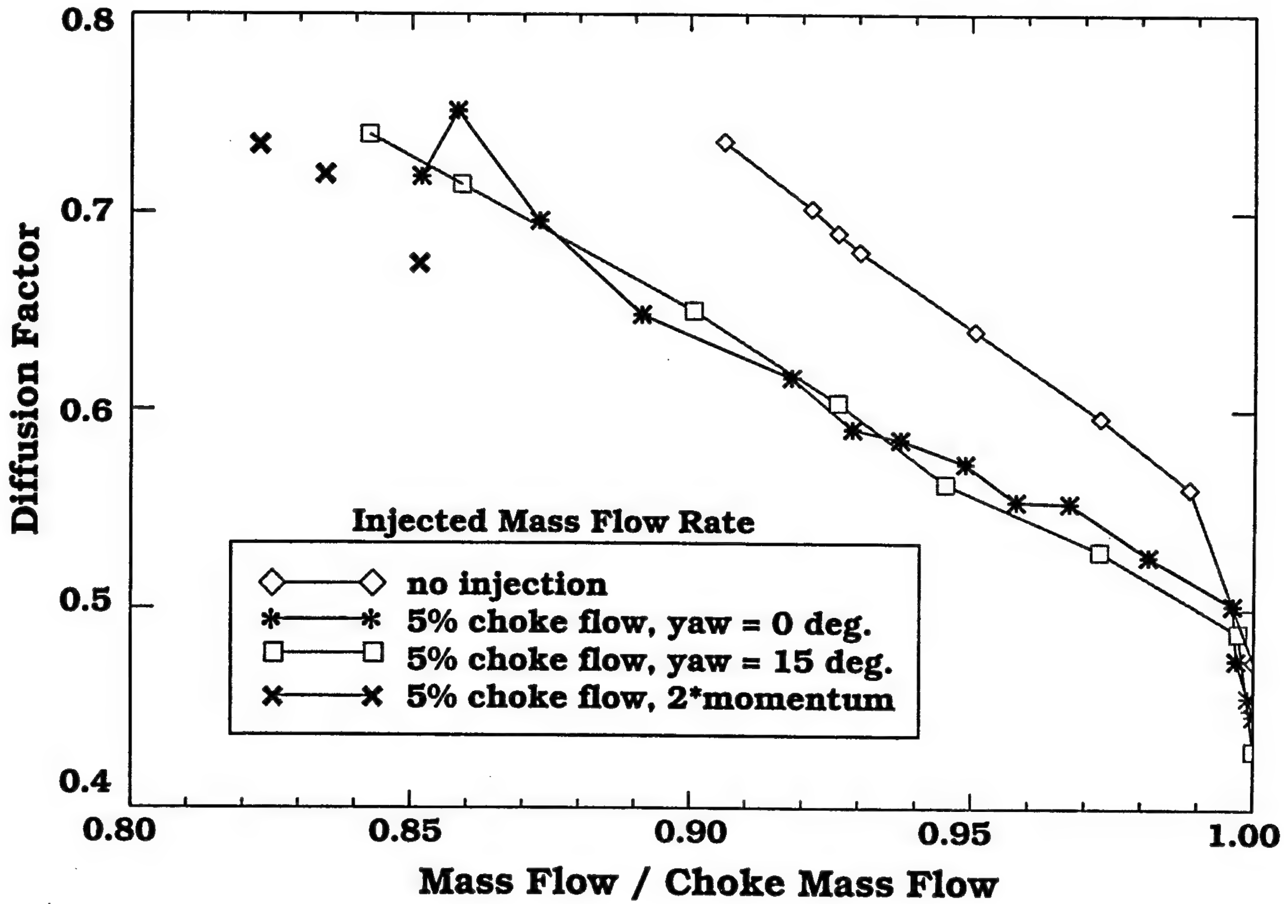


NASA Stage 35 Stability Enhancement for Radial Distortion
Comparison to clean-inlet performance
Utip=1265 ft/sec (85% design speed)



Average-Passage CFD analysis indicates steady tip injection reduces blade tip loading

D-factor at 98.5% span as a function of injection parameters



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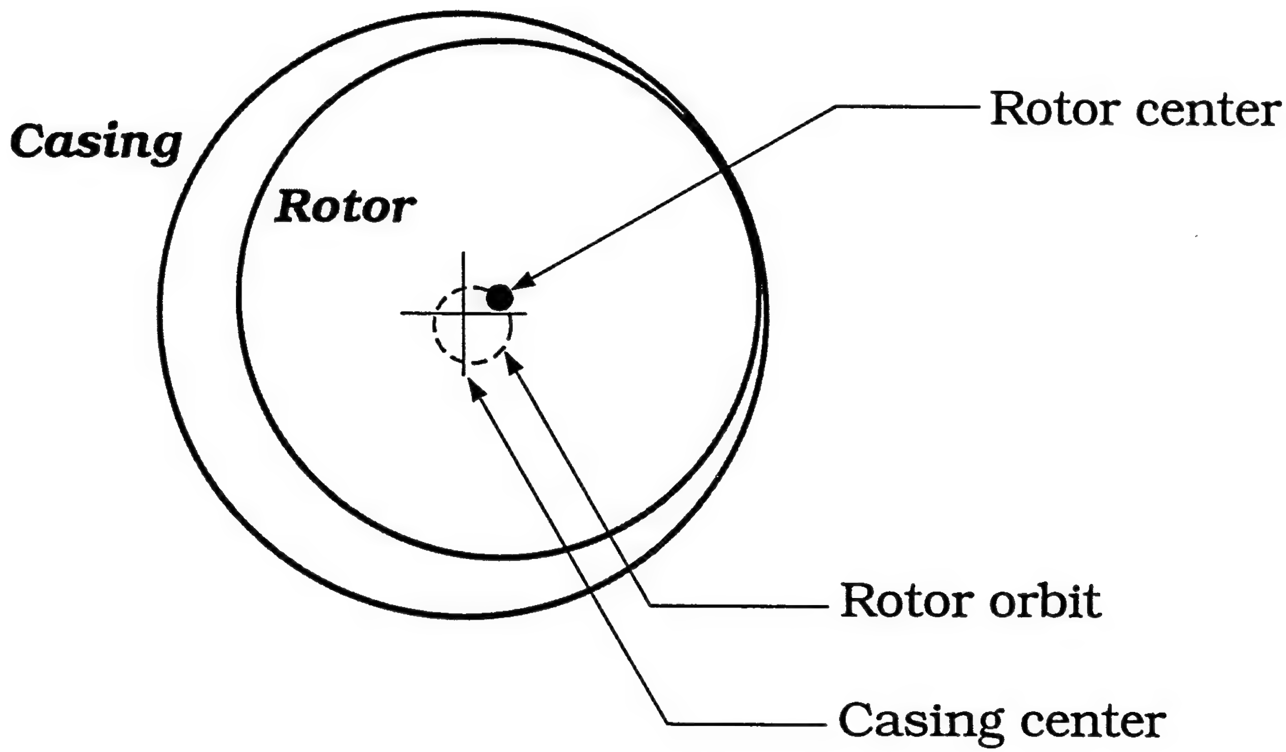
Stability Enhancement via Magnetic Bearings

Ken Gordon/Choon Tan, MIT

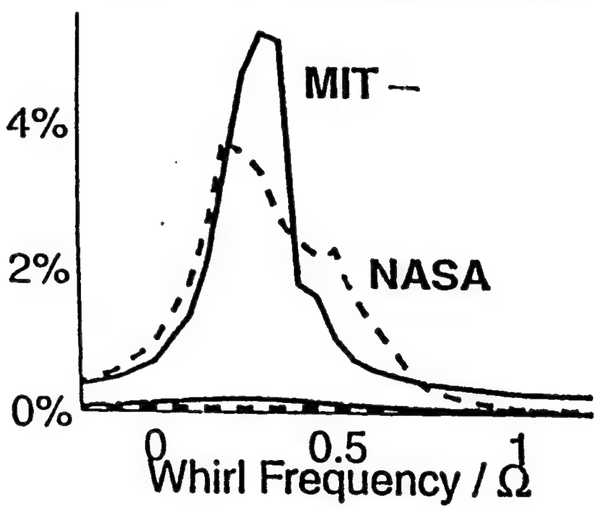
- ***Assume rotor & casing not out-of-round***
- ***Rotor shaft orbit not centered in casing***

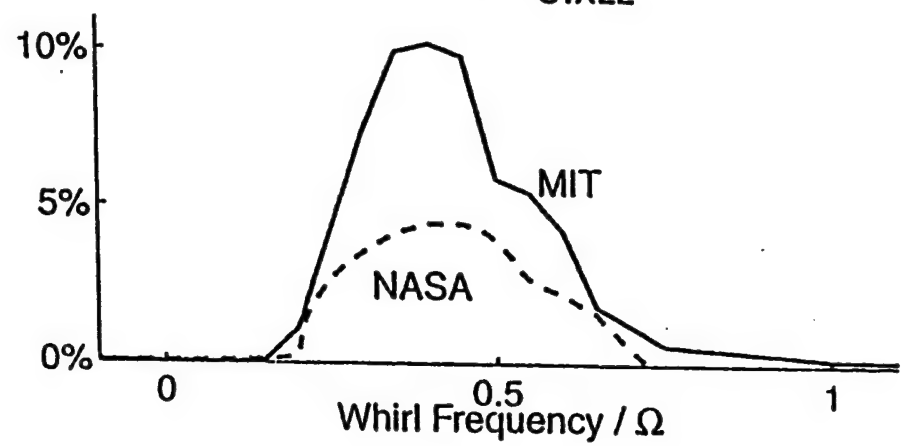


Stability Enhancement via Magnetic Bearings

Assess Impact of Shaft Whirl on Compressor Stability

Low-speed 3-stage, transonic single stage
Shaft offset = 50% of rotor tip clearance





- Severe loss of stability when whirl freq = rotating stall freq
- Offset shaft couples circumferential harmonics
- With offset shaft, mag bearing can impact higher harmonics

Active/Passive Control of Stall in Axial Compressors

Y. Neumeier, J. Prasad, M. Lal, S. Bae, A. Meehan

School of Aerospace engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150

Workshop on
Goals and Technologies for Tomorrow's Gas Turbines

Atlanta, Georgia
June 15-16, 1998

Compressor Control Research at Georgia Tech

Facilities

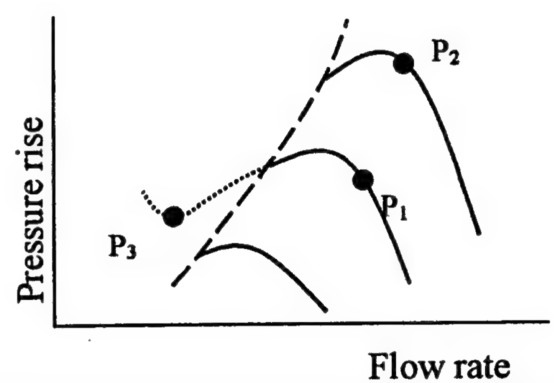
- **Axial compressor rig**
- **Centrifugal compressor rig (under development)**
- **Combustor-turbo charger setup**

Scope of Activities

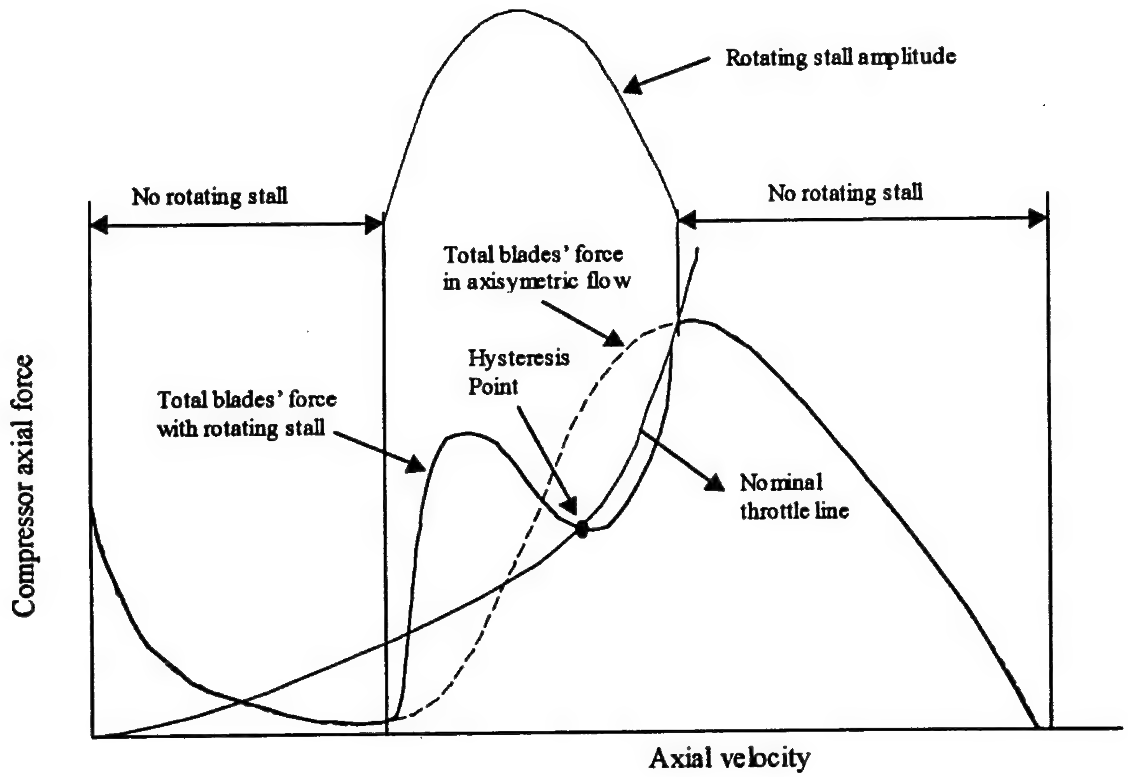
- **Modeling**
  - **CFD**
  - **Control oriented models**
- **Control Methodologies**
  - **Robust control**
  - **Fuzzy Logic control**
- **1-D Control actuators**
  - **Bleed valve**
  - **Recirculation**
  - **Fuel injection**
- **Passive Control**

Essentials of Rotating Stall and Surge in Axial Compressors

- Compressor at p_1
- Increase fuel to accelerate rotating speed to desired operation at p_2
- The pressure in the combustor increases too fast while turbine acceleration is too slow, the compressor stalls at p_3



Essentials of Rotating Stall and Surge in Axial Compressors (continued)



Local Versus Global Actuation

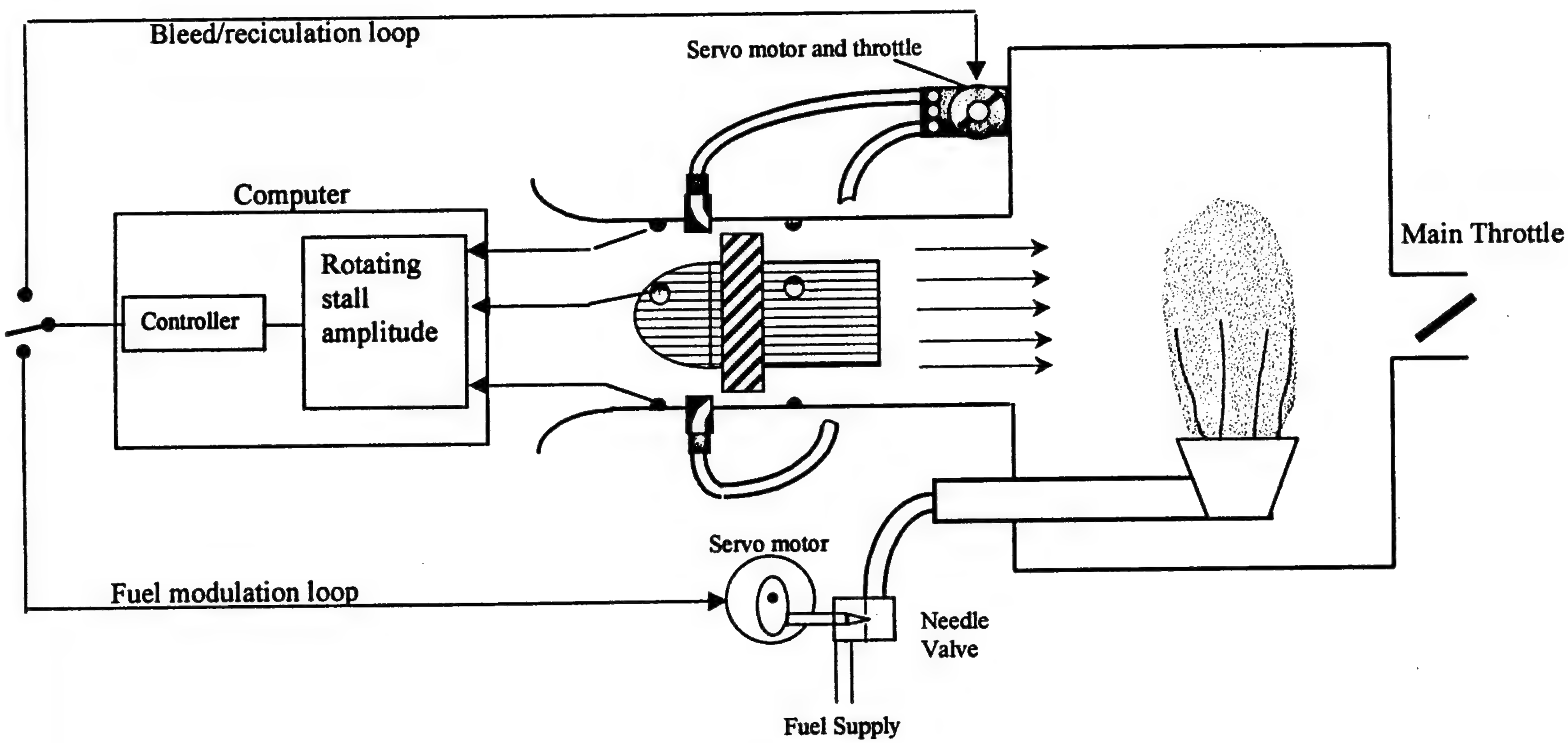
Local actuation

- Actuators must respond on a time scale of the rotating stall frequencies (100's Hz)
- Utilizes vanes and injection valves in inlet
- Largely decoupled from axial (bulk) flow dynamics

Global actuation

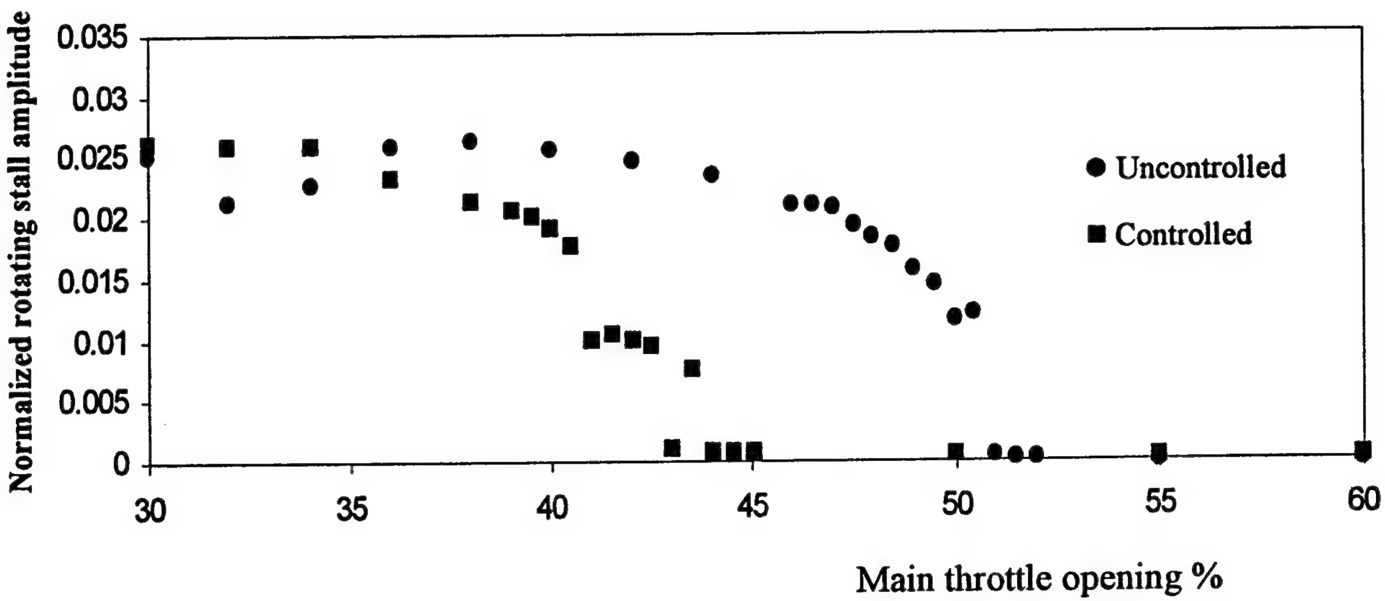
- Introduced in inlet, outlet, or plenum
- Uses bleed valves, recirculation, or fuel modulation (combustor)
- Couples with axial (surge like) flow oscillations

Experimental Setup

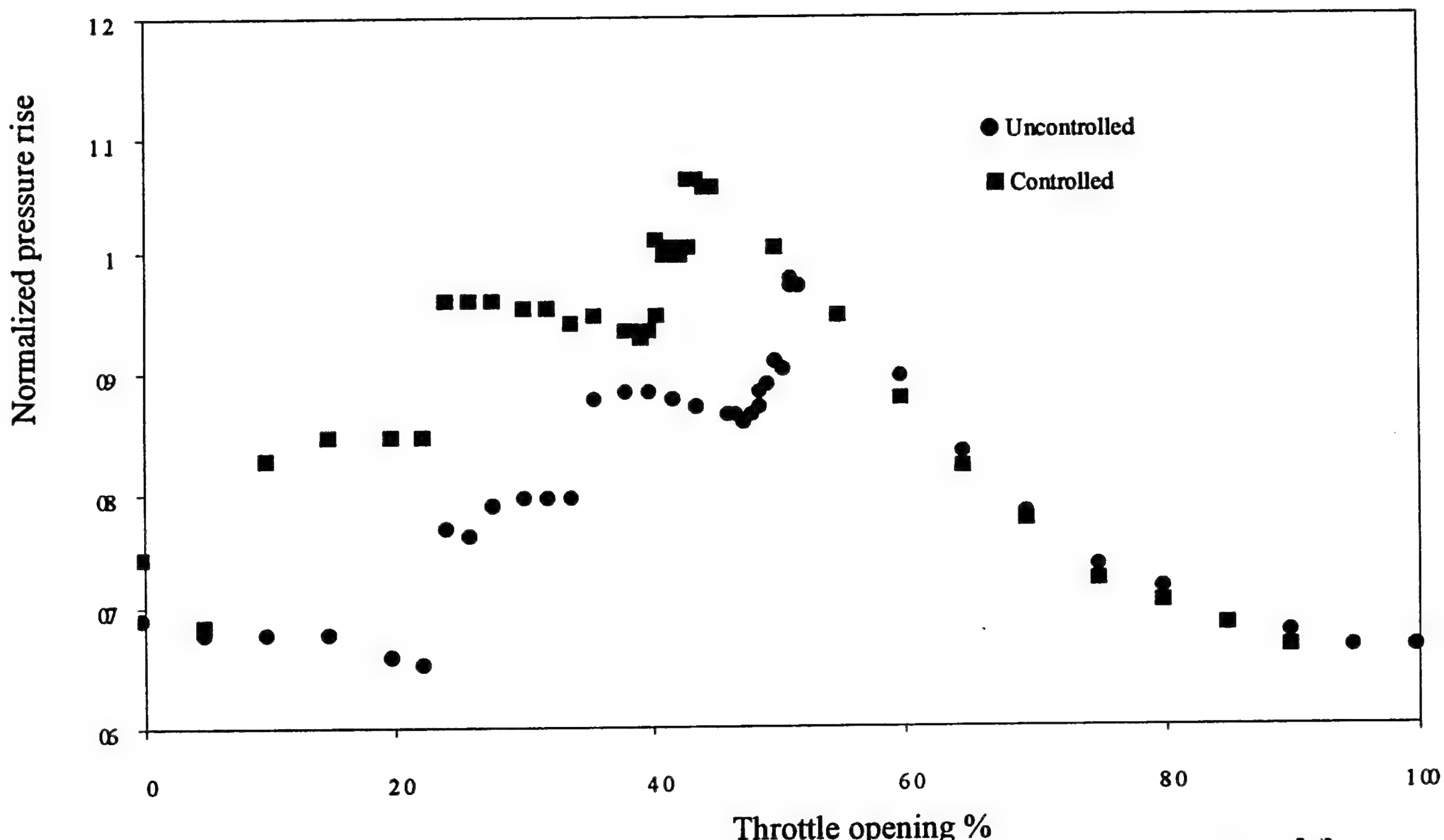


Control with Recirculation

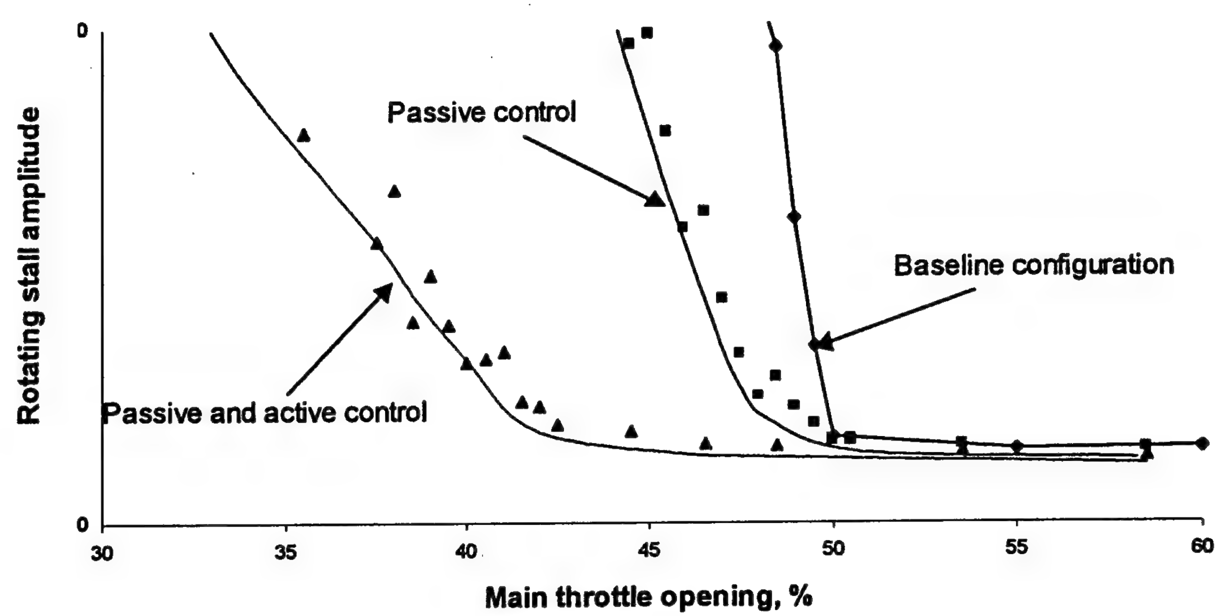
- Combines two effects
  - -Reduces pressure in plenum (bleed)
  - -Increases velocity on blades' tips



Control with Recirculation (continued)



Passive Control Consideration

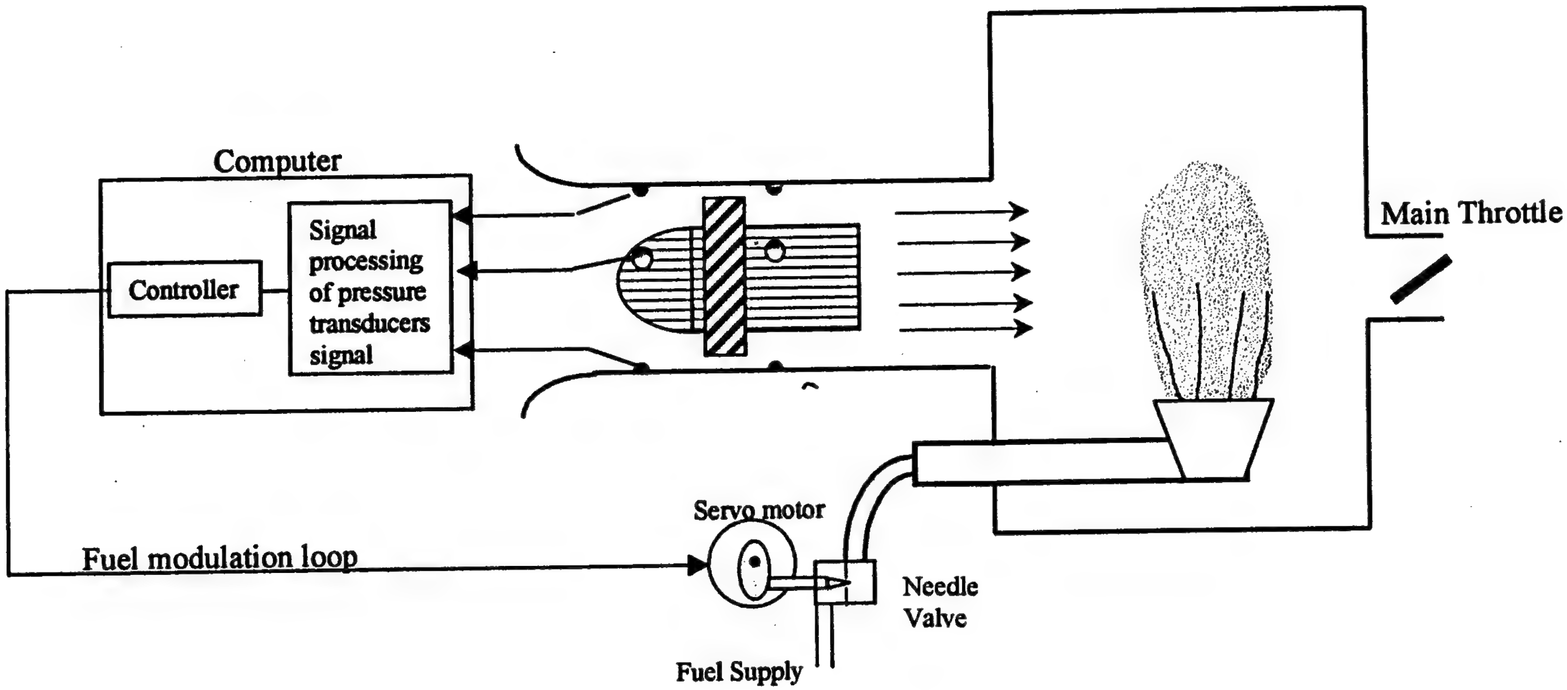


- Passive means can be used to improve the uncontrolled compressor stability and enhance the performance of the active control system

Compressor Control Via Fuel Modulation; Motivation

- Unified fuel authority for control of combustor and compressor will allow fast transition from one operating point to another and enhance disturbance rejection
- Fuel provides the most "powerful" means for altering the mean flow rate through the compressor
- No energy waste around the nominal operating point
- The dynamic response of existing fuel injection systems may be adequate

Fuel Modulation Setup



- Diffusion flame simulates heat release in a real engine combustor
- Operating point around 300 ^{0}F
- Limited combustion process heat release response (about 10 Hz)

Fuel Modulations; Preliminary Results

- Heat release in the plenum significantly alters the compressor flow dynamics
- Natural flame oscillations push the compressor in and out of rotating stall (not expected in real gas turbines)
- Fuel modulations appear to be a viable means for stall suppression

Accomplishments Under the MITE Program

- Significant corrections to the theory of rotating stall control with amplitude feedback
- Modification of the theory of modal rotating stall
- Experimental demonstration of rotating stall control with 1-D throttling
- Experimental demonstration of rotating stall control with 1-D plenum-inlet recirculation
- Experimental demonstration of rotating stall control with combustion process modulations
- Demonstration of rotating stall suppression with passive means

Research Directions

- Theoretical investigation of the feasibility of fuel control
- Studies of stall and surge in centrifugal compressor
- Modification of the axial compressor setup to include
  - means for altering compressor characteristics
  - means for inducing a sudden cell stall using sparks or impulsive jet injection at discrete points around the compressor
  - means for driving persistent rotating stall with upstream disturbances in the rotating stall frequency
- Investigation of a coupled axial-centrifugal system

Aero-Thermal Design and Analysis of Gas Turbine Combustion Systems Current Status and Future Direction

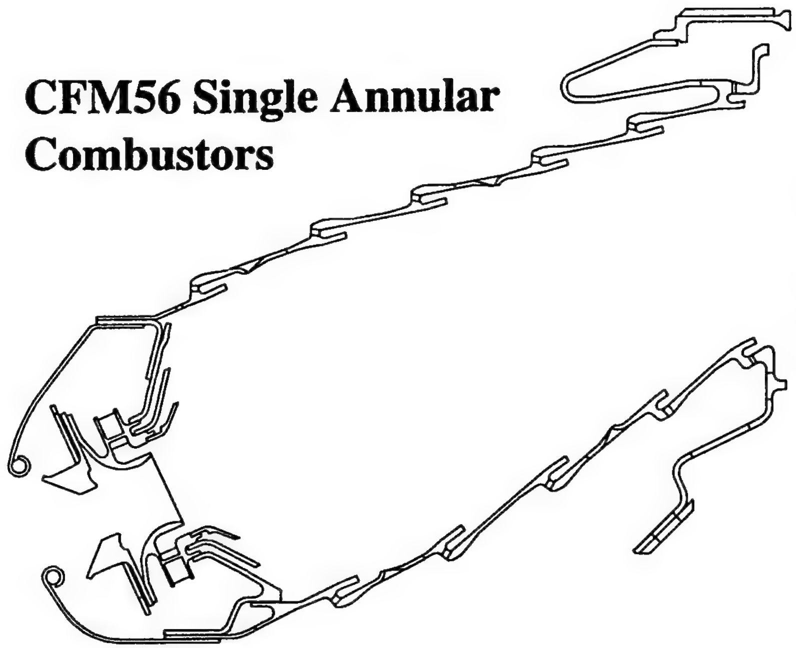
by

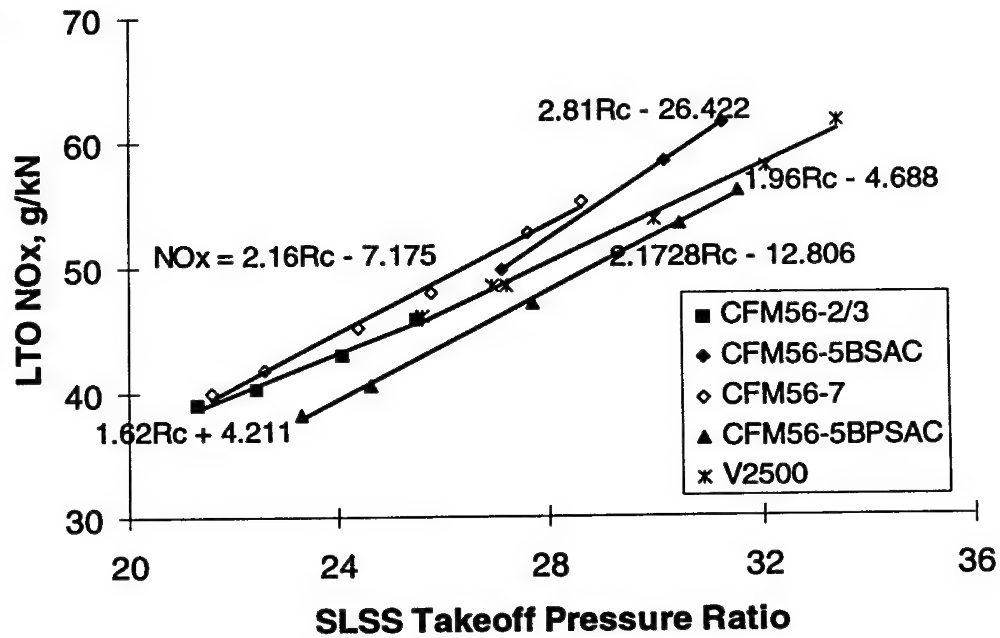
Hukam C. Mongia

Combustion Center of Excellence
GE Aircraft Engines
Cincinnati, Ohio

GE Aircraft Engines (GEAE) has introduced several new aeropropulsion gas turbine engines with improved combustion systems since 1994 including the CFM56 dual annular combustor (DAC), the CF6-80 low-emissions single annular combustor (LEC), the GE90 DACII, in addition to the dry low emissions (DLE) for the LM1600, LM2500 and the LM6000. GEAE has also made significant progress in the development and application of the semi-analytical mechanistic (SAM) models and anchored CCD during the combustion design and development process as described in this paper. GEAE is working with NASA in the development and validation of advanced turbulence and radiation models as part of the National Combustor Code (NCC). These activities have benefited the GEAE combustion design process which now uses routinely both the SAM and CCD-based methods unlike the most conventional "cut-and-try" design practice.

CFM56 Single Annular Combustors



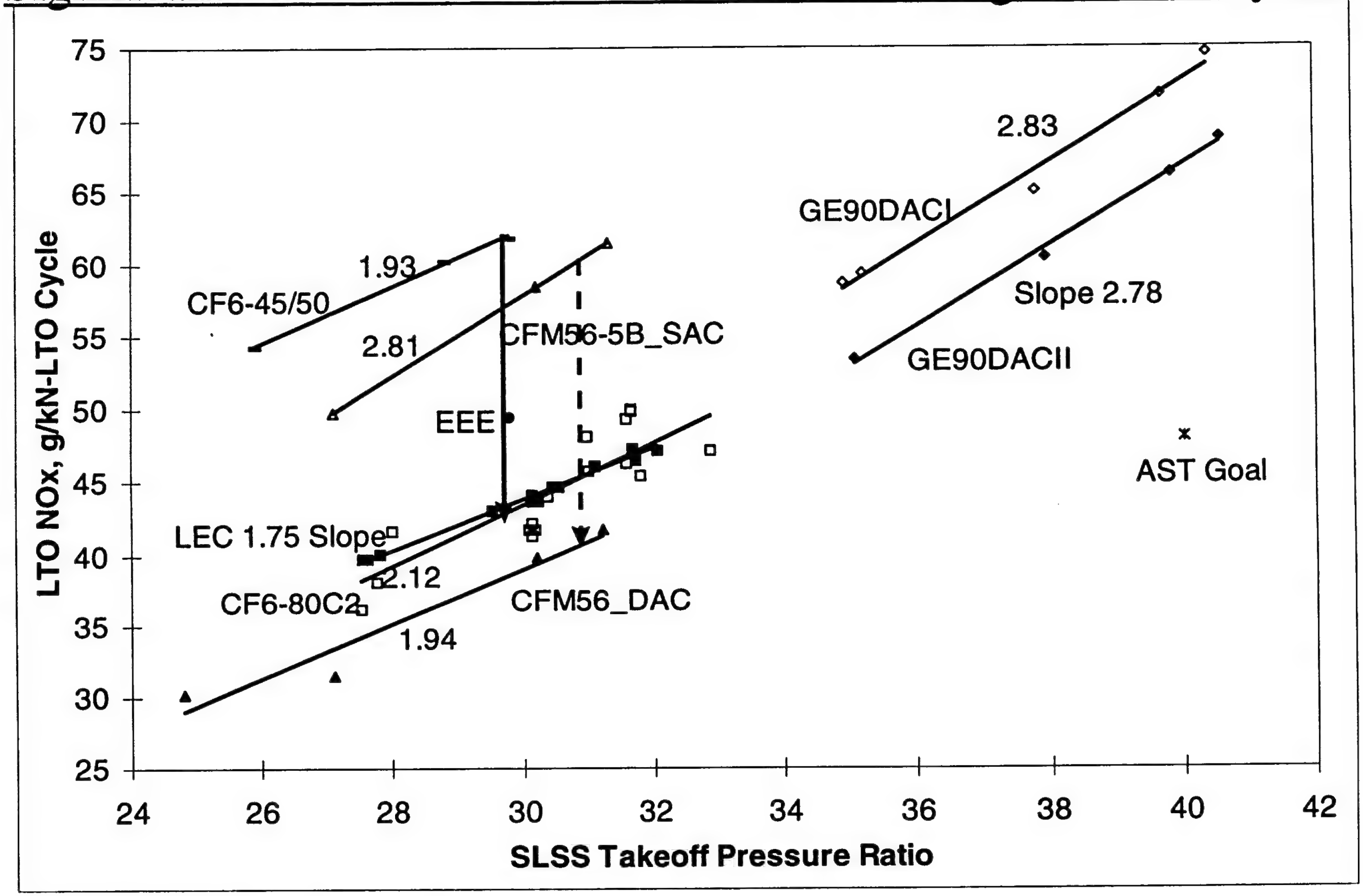


•The latest model, the CFM56-7B emissions certification in July 1996

•LTO NOx of the CFM56-5BP (Improved Performance) 9% lower than that of the CFM56-7 w/ the same combustion technology - due primarily to the SFC improvement

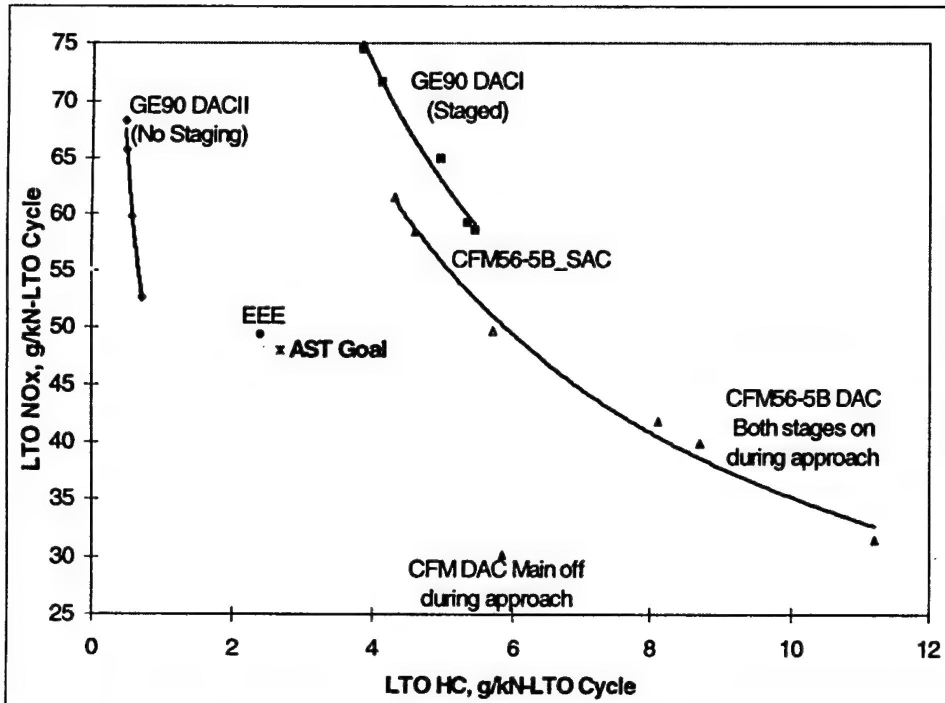
•SFC (CO_2) reduction will result in NOx reduction offset (to some degree) by increase in operating pressures and temperatures - New Emissions Reduction Technology!!!!

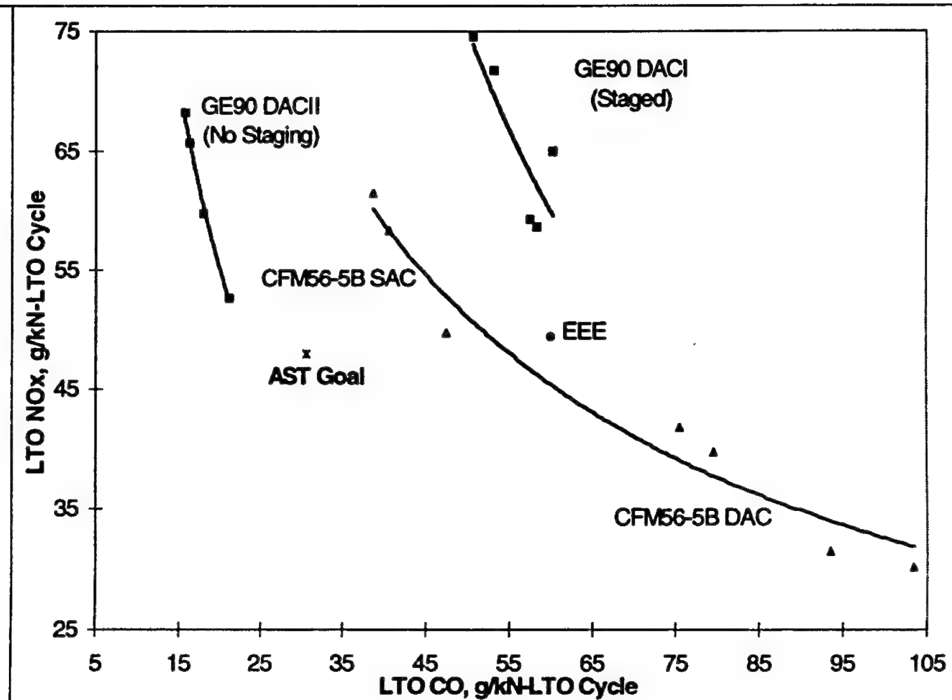
Significant Emissions Reduction Achieved during the last 20 years



AST Technology for further reduction in NOx, CO and HC

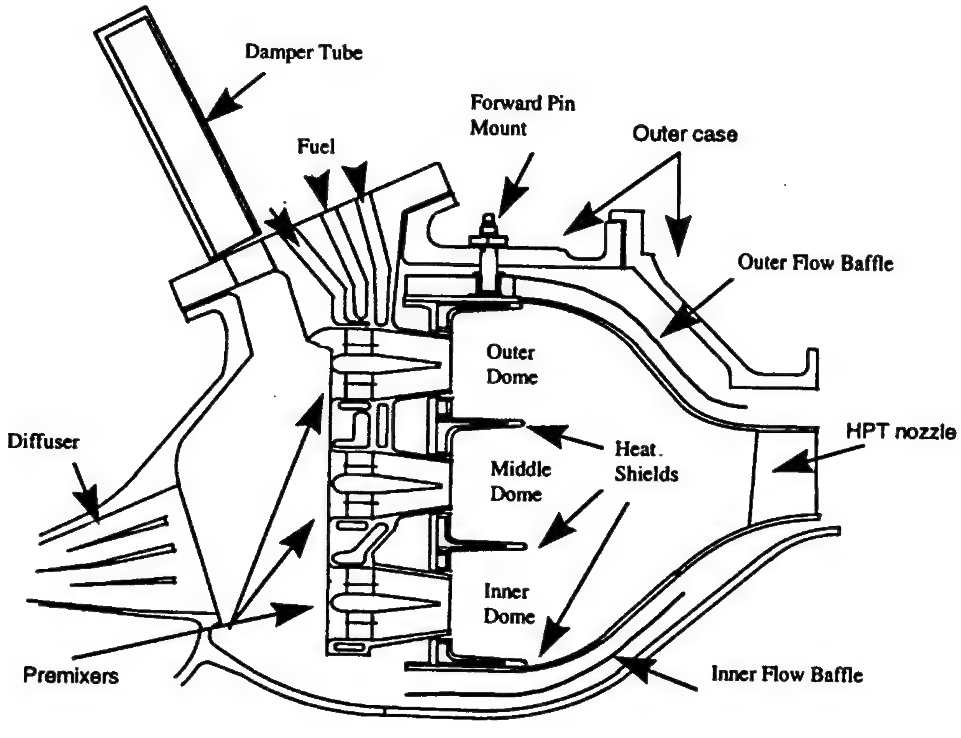
- TAPS for 50% below ICAO NOx (32+1.6 Takeoff Pressure Ratio)
- AMI for 70% below ICAO NOx

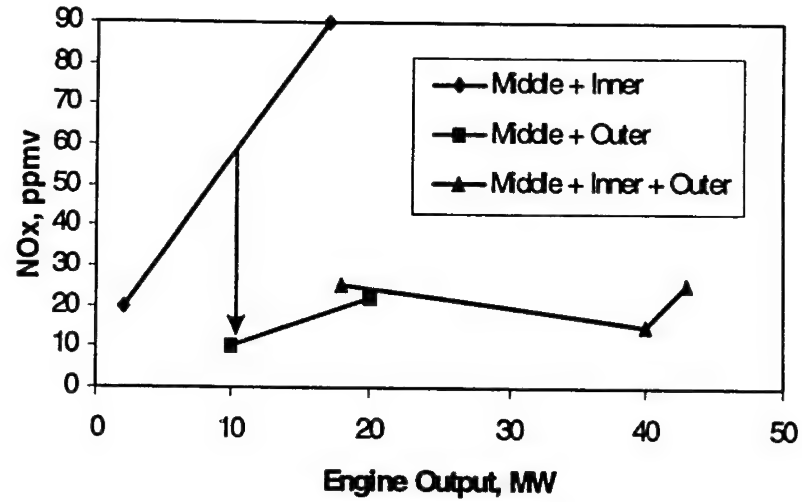


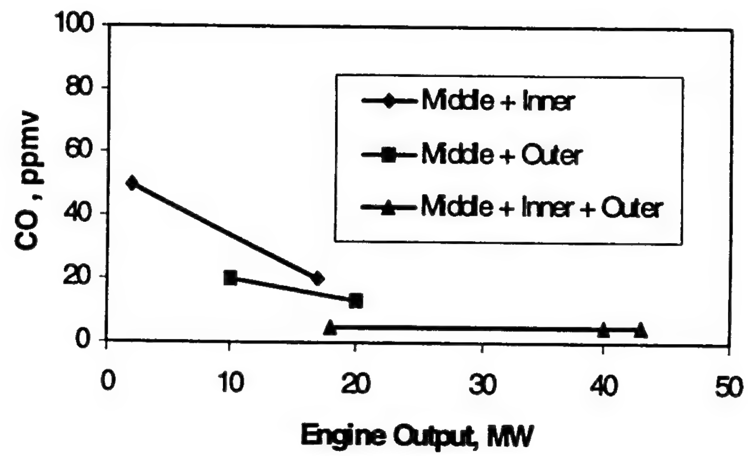


Aero-Derivative Dry-Low Emissions Give Low Emissions over a wide power operating range

	LM16000	LM2500+	LM6000
Power MW	15	29	44
Thermal Efficiency	37%	39.1%	42%
Air flow KG/Sec	43	77	125
Pressure ratio	22	22	30
Nominal Firing temp °C	1290	1290	1290
NOx/CO Emissions Requirements			
Synchronous idle		35/300	40/200
25% power		40/50	40/50
50% power	<50/25	<25/20	<25/20
100 % power	<25/20	<25/20	<25/20







Evolution of Combustor Design Methods

Tools for Preliminary Design, Data Reduction/Analysis

- Empirical
- Semi-empirical
- Semi-analytical
- Semi-analytical mechanistic (SAM) (Extension of Tonouchi & Pratt (95) multiple reactor network for jet-stirred to gas turbine combustors w/ PSR/PFR, Tonouchi, Held & Mongia, 1997, Held, Mongia & Tonouchi, 1998.

Computational Comb Dynamics for Detail Design/Analysis

- Qualitative Guidance started 1975
- Hybrid modeling, Rizk and Mongia (86, 90 91, 93, 95)
- Anchored CCD, Danis, Burrus & Mongia (96)

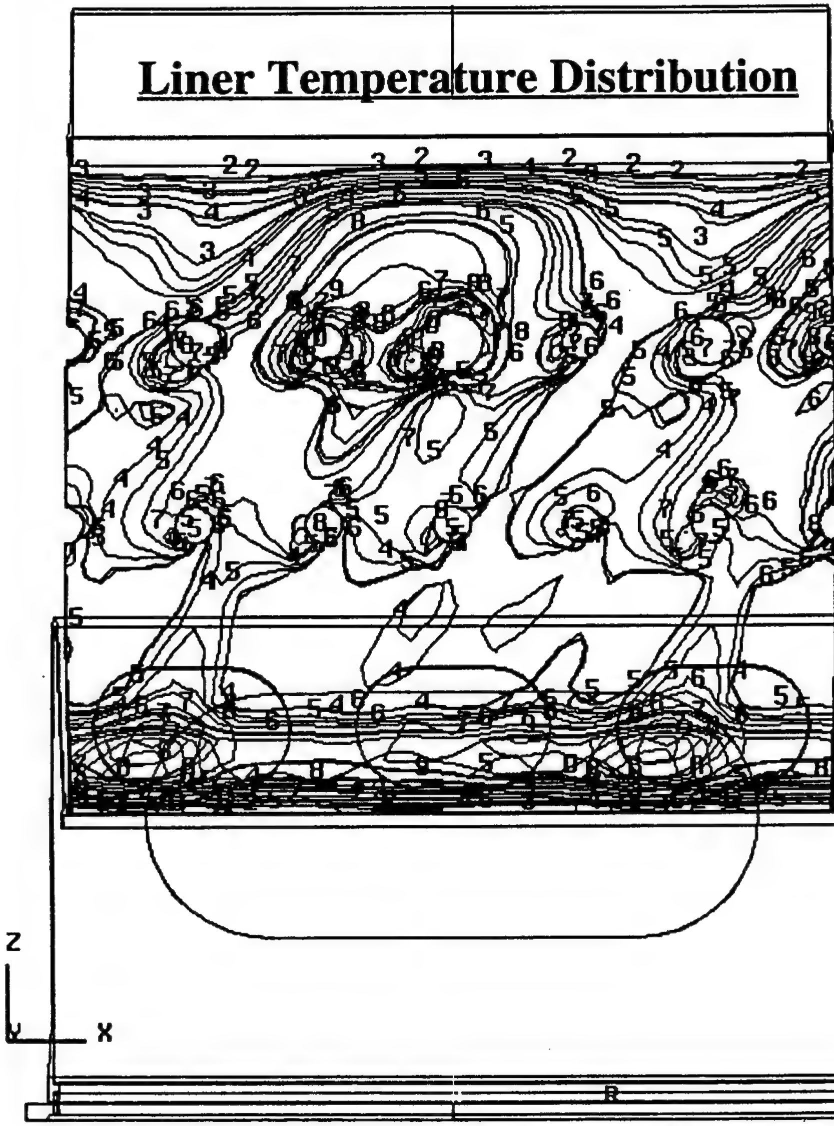
- Feasibility demonstration for next-generation design tools
  * Laminar flamelet for DLE w/ GRI2.11 mechanism, Held and Mongia (98a,b)
  * Dynamic model for DLE, Hsiao et al. (98)
  * Advanced turbulence, radiation and spray models, Nikjoo et al. (98), Kumar et al. (98), Aggarwal et al. (98a,b)
  * Comprehensive fuel/air preparation model
  * Large eddy simulation for DLE
  * Chen's scalar PDF w/ reduced kinetics

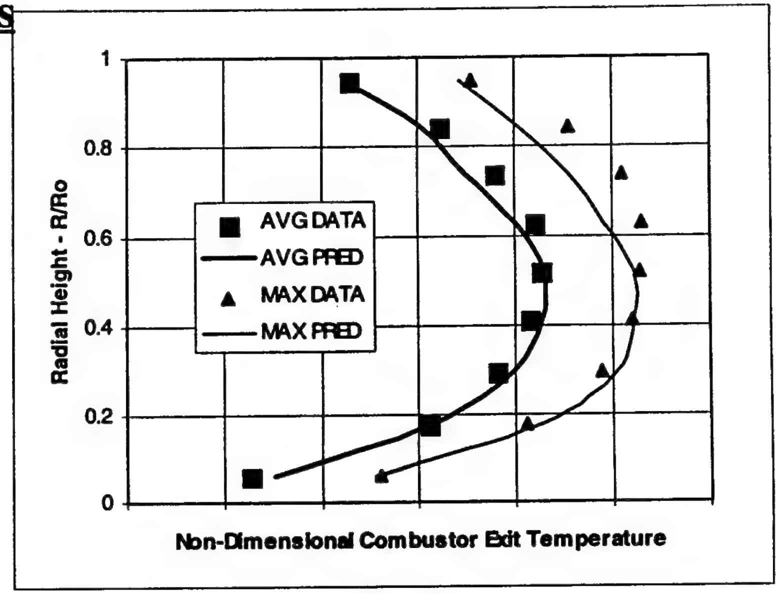
Accuracy Goals and Current Status of SAM and CCD Tools

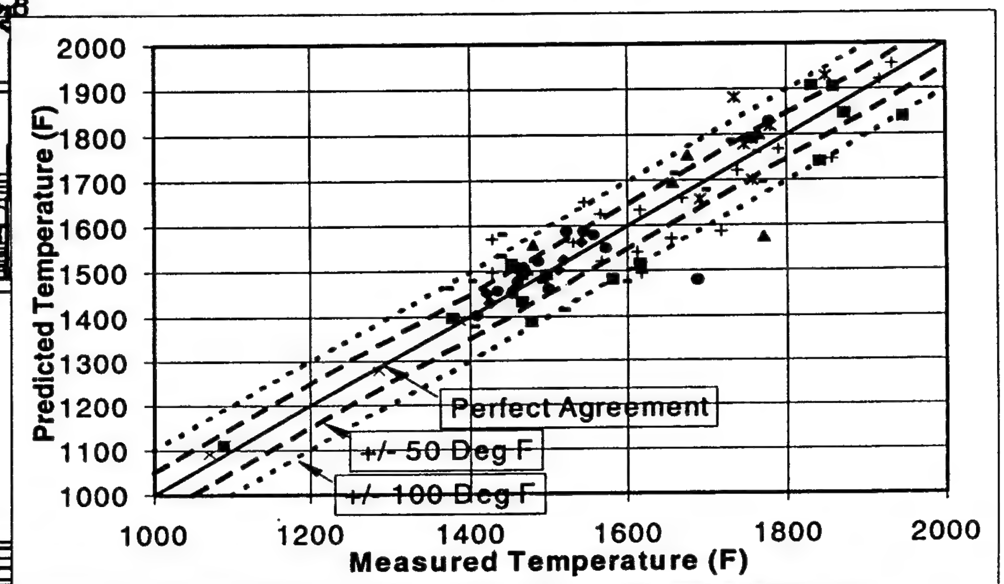
Variable	Predictive accuracy band
NOx	± 5 %
CO and unburned hydrocarbons	± 10 %
Exhaust SAE Smoke Number	± 2
SLS idle lean blowout fuel/air ratio	± 0.001
Pattern factor (Peak Profile Factor)	± 0.03
Average radial profile factor	± 0.015
Maximum liner wall temperature	± 25^0 F
Combustion system pressure drop	± 0.25 (% Pt3)
Diffusion system pressure drop	± 0.125 (% Pt3)
Circumferential location of the liner hot spot	± 0.1 × Nozzle sector
Axial location of the liner hot spot	± 0.01 × Comb. length

COMBUSTOR	AVERAGE ENGINE LTO:	ICAO DATA (g/KN)	ANCHORED PREDICTION (g/KN)
GE90-92B DAC-2	NOx	70.7	70.7
	CO	14.4	13.8
	HC	0.5	0.4
	SMOKE	0.5	-
GE90-92B DAC-1	NOx	73.1	67.2
	CO	55.5	29
	HC	4.4	9.9
	SMOKE	9.3	-
CF680C2 LEC	NOx	46.5	44.4
	CO	23	-
	HC	1.8	-
	SMOKE	6.9	-
CFM56-5B SAC	NOx	61.5	58.5
	CO	38.6	-
	HC	4.3	-
	SMOKE	10.1	-

Anchored Aero-Thermal Analysis (ATMA) Status



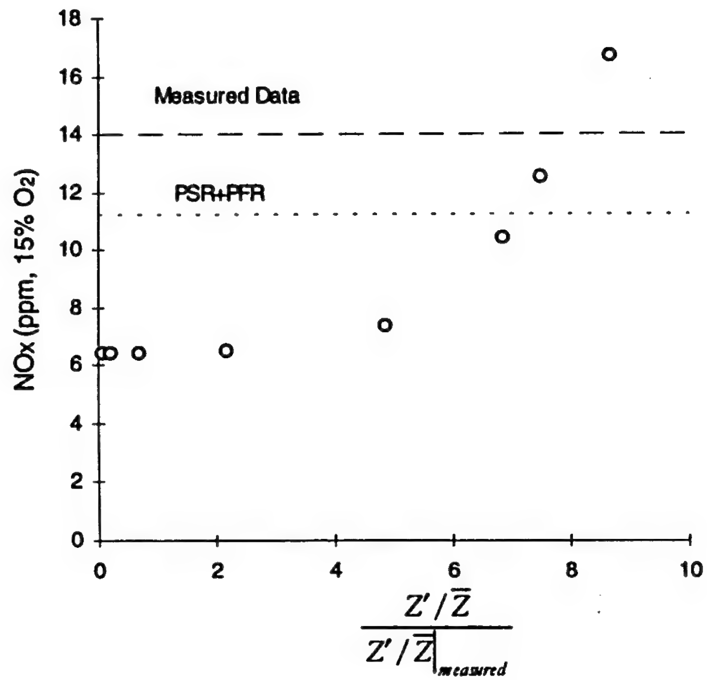


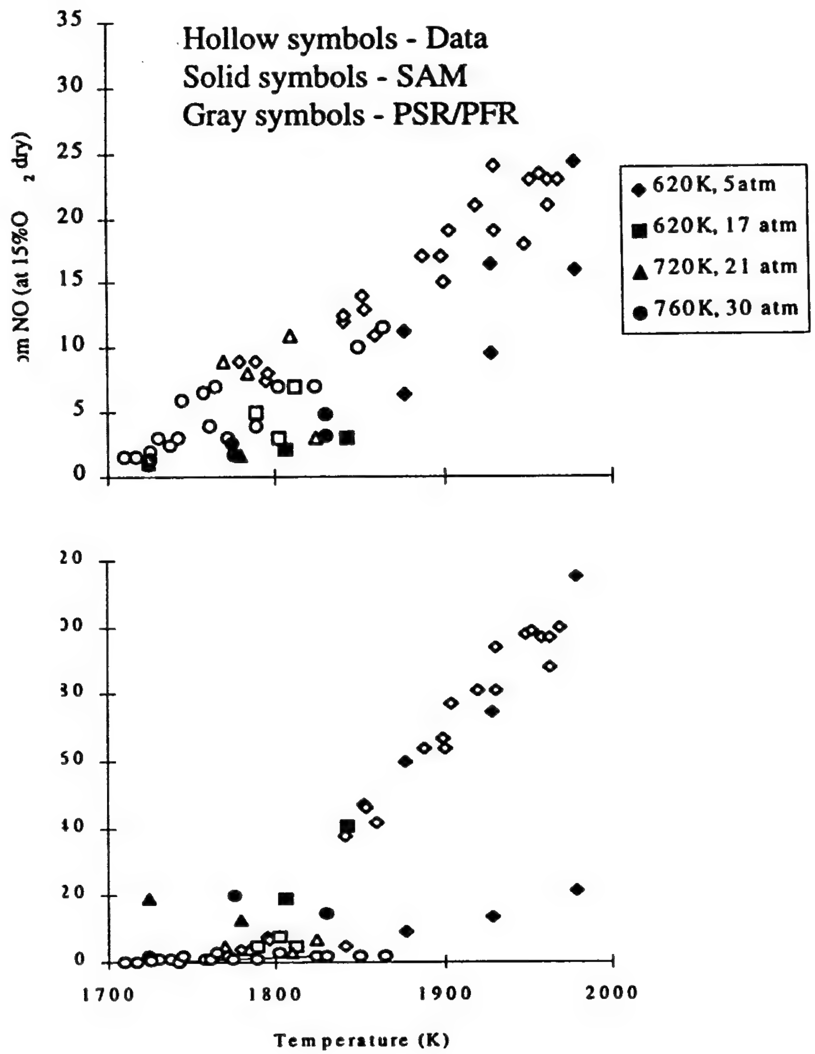


Semi-Analytical Mechanistic model for Dry-Low Emissions

Monte Carlso simulation of PaSR/PFR that takes into consideration:

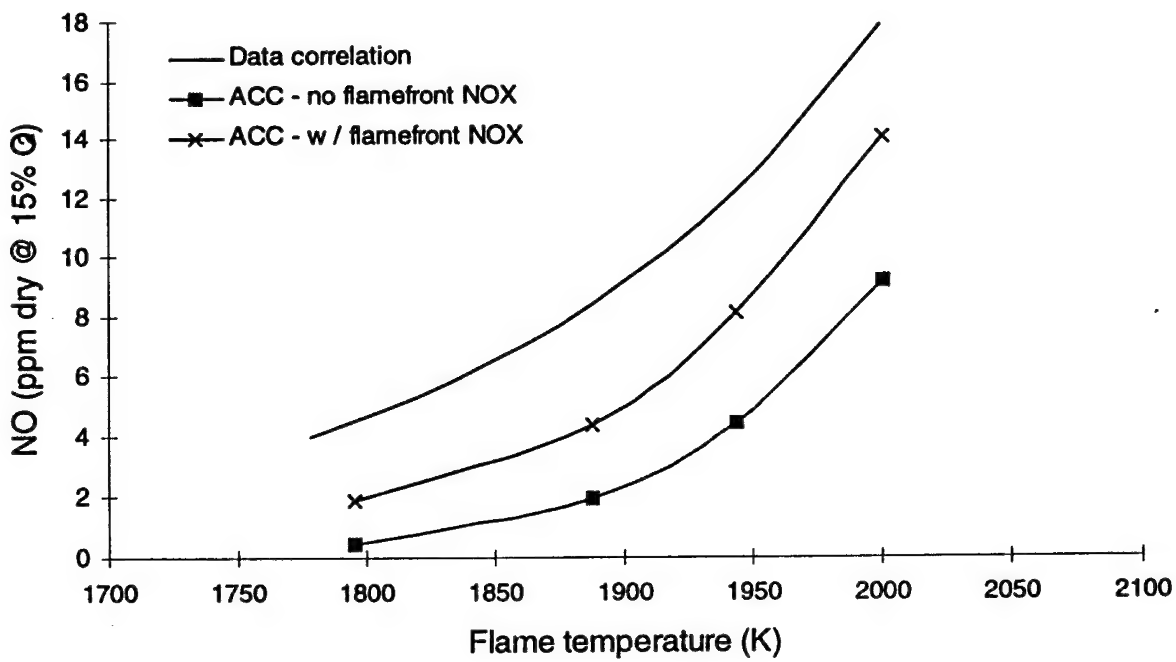
* Unmixedness of the inlets
* Finite rate large/small scale mixing
* PDF around the mean residence time
* Airflow distribution





Partially Premix Laminar Flamelet Modeling for DLE

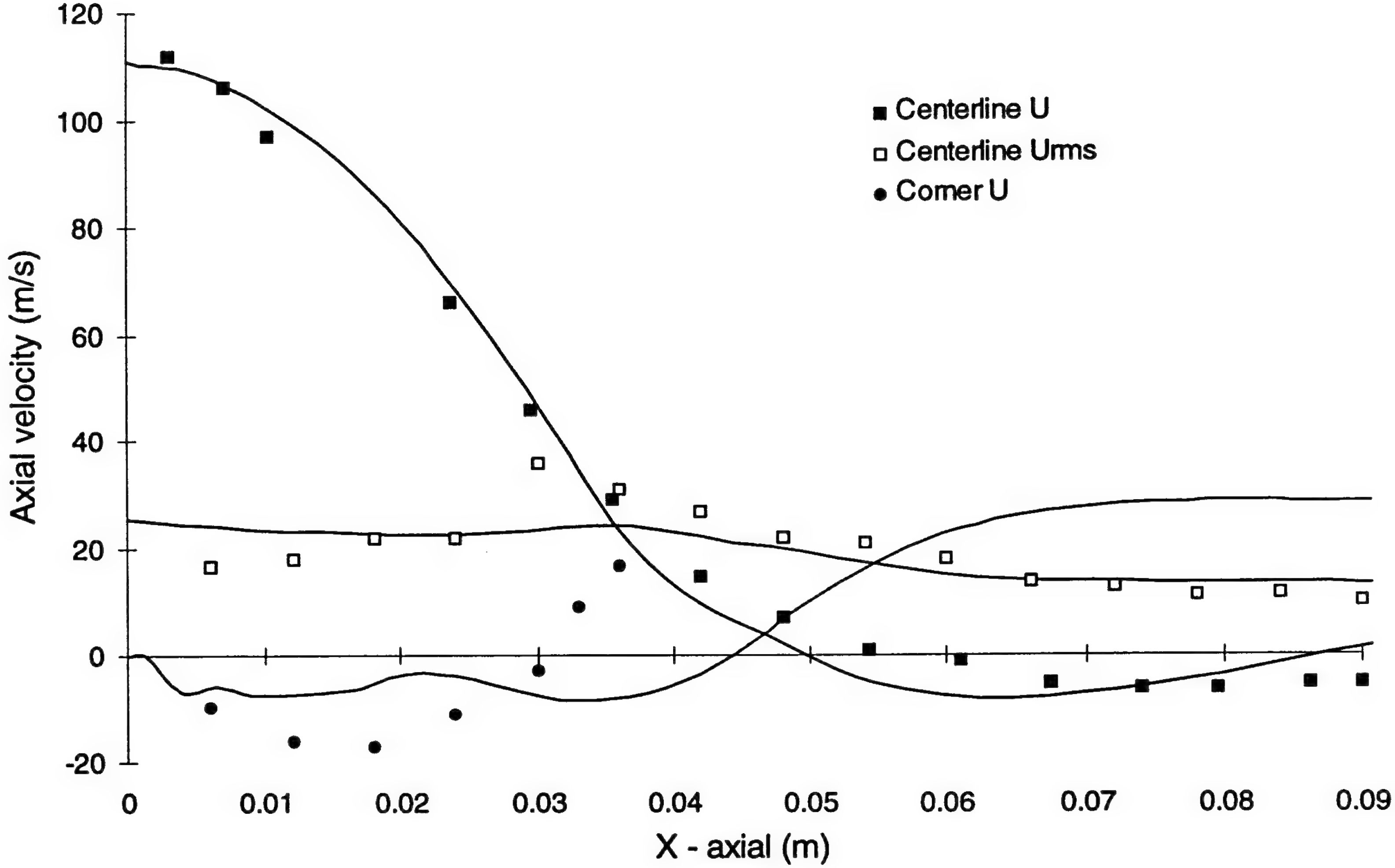
- GRI 2.11 kinetic scheme
- 3-D calculations for Aero-derivative DLE fuel/air mixer
- Realistic modeling for NO and CO predictions
- Computer time comparable with 2-step eddy breakup model
- Good agreement between predicted and measured field characteristics and emissions



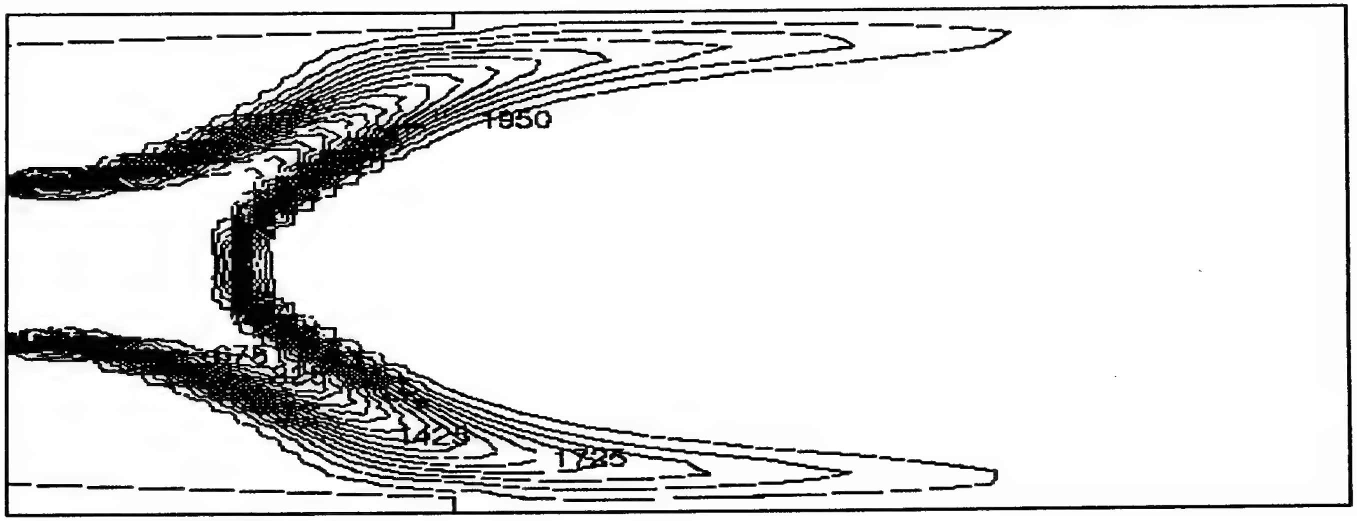
Laminar Flamelet Modeling

Centerline and corner axial velocity profiles

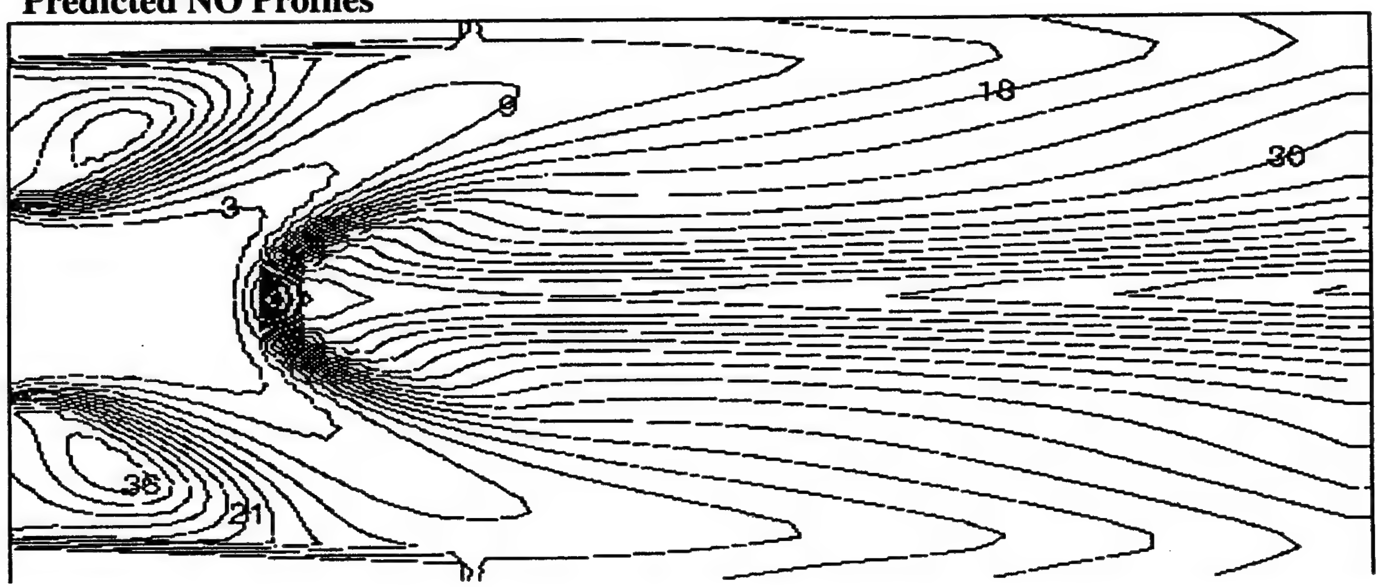
LM6000 single cup rig



Laminar Flamelet Predicted Temperature Distribution for the LM6000 DLE Single Cup



Predicted NO Profiles



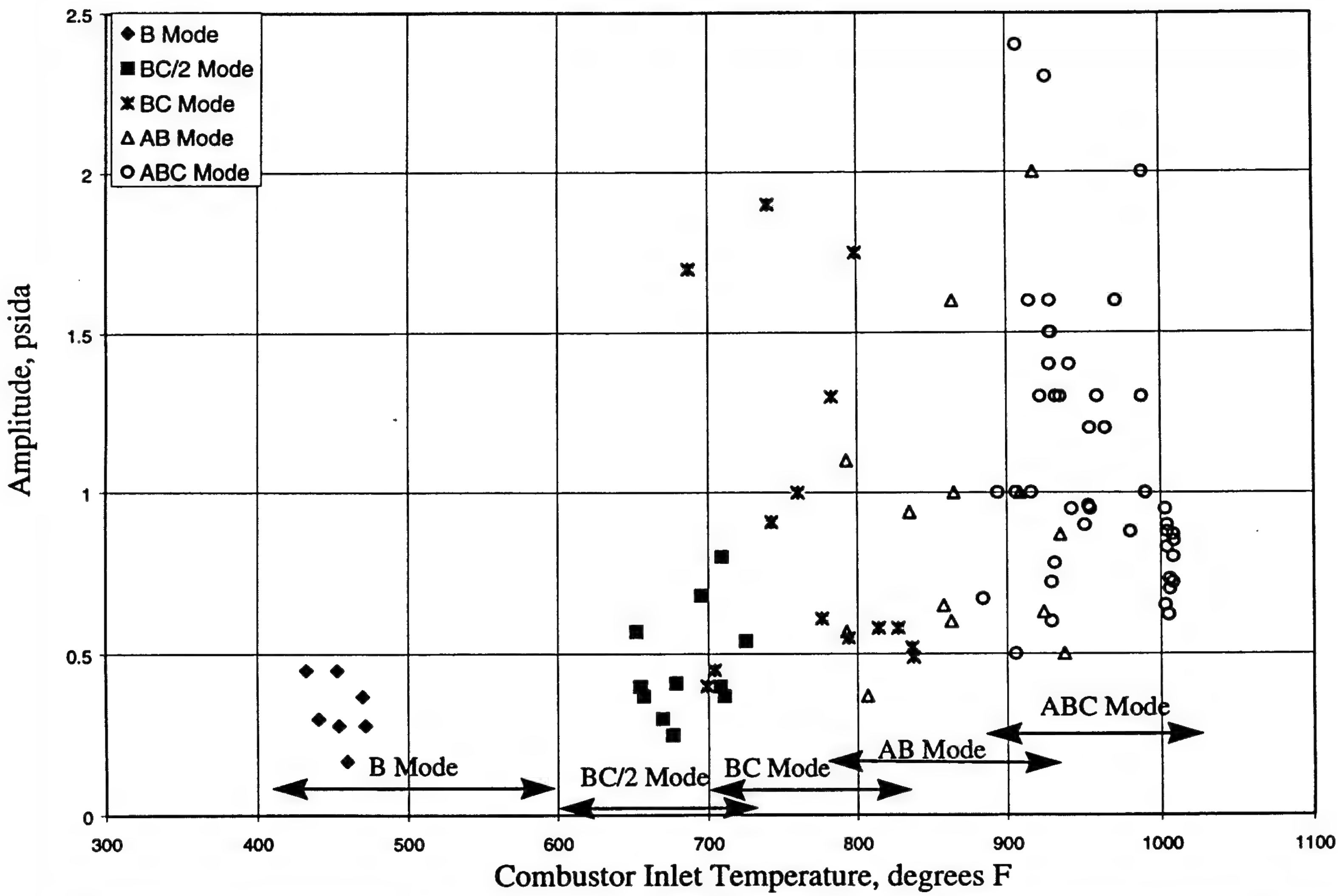


Figure 13. Instability Characteristics of DLE Combustor (Data from Seven Production Engines)

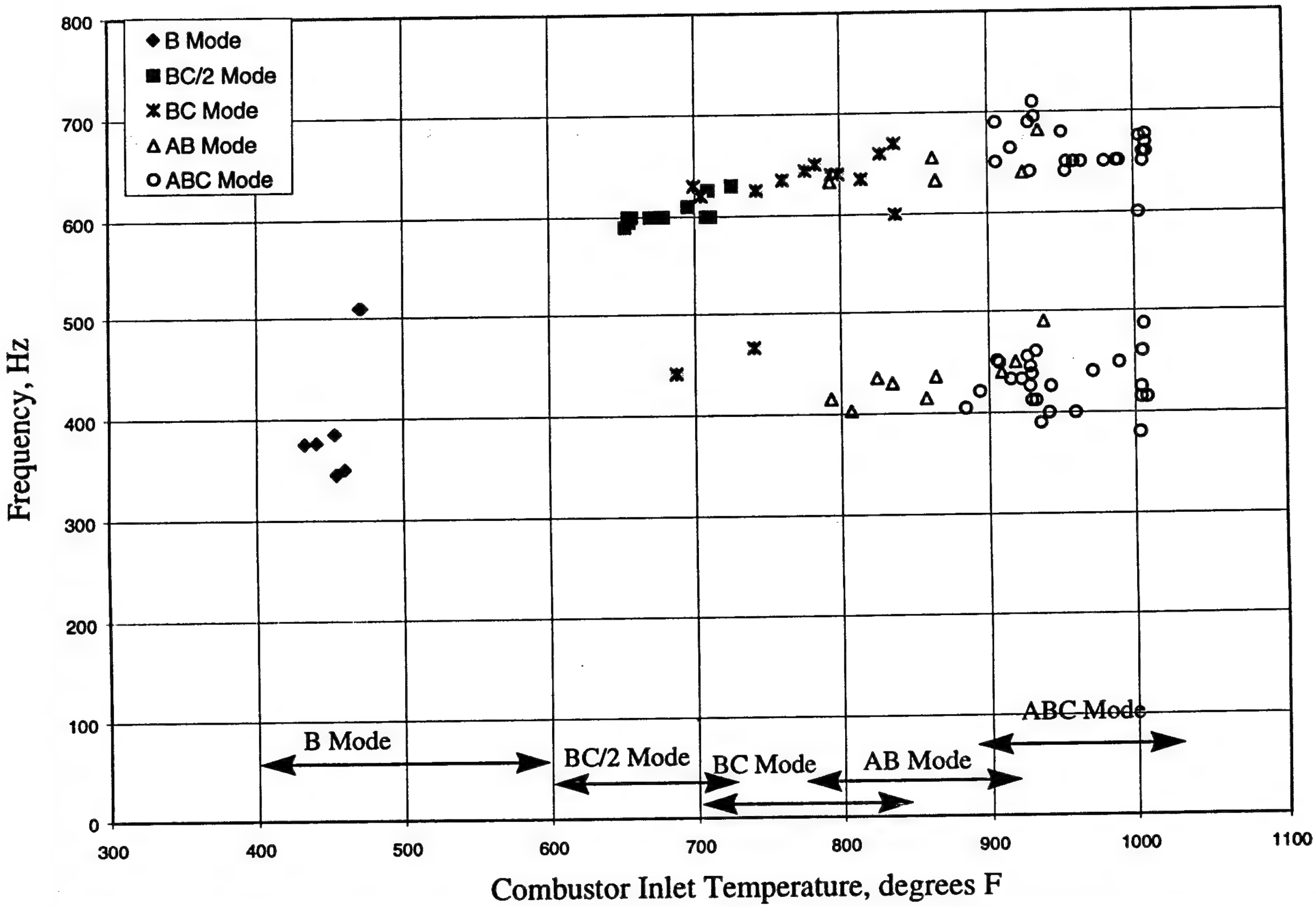
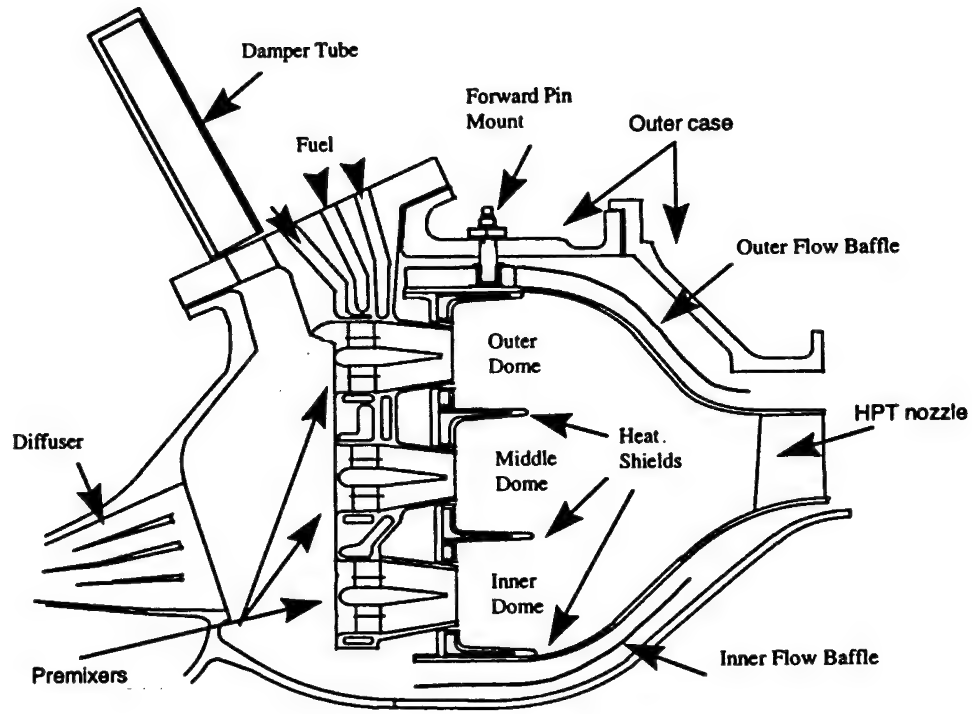


Figure 14. Instability Characteristics of DLE Combustor (Data from Seven Production Engines)

Combustion Dynamics is "a System Issue"

1. Combustion System 2. Boundary Conditions (Compressor and Turbine), 3. Fuel Injection System, 4. Controls

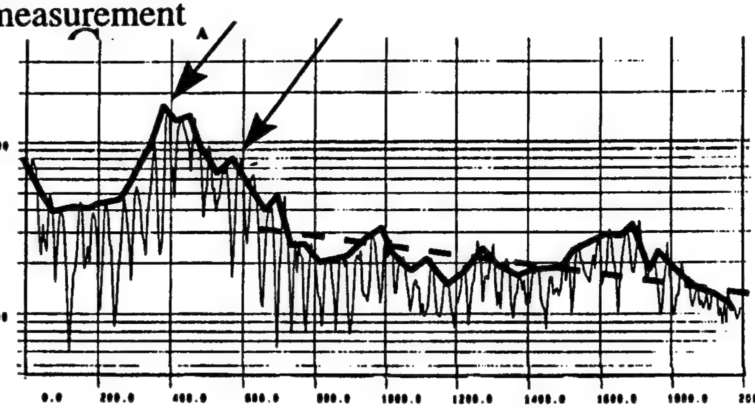


Preliminary validation completed of acoustic modeling in regard to:
1. Compressor and turbine nozzle interfaces; 2. Damper tubes; 3. Fuel system; 4. DLE mixer

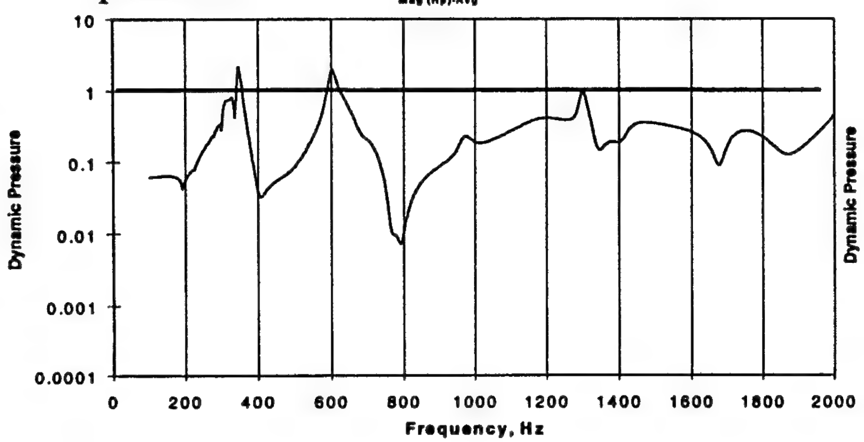
Prediction of Acoustically Active versus Inactive Modes
(Effect of Circumferential Non-uniformity)

• Dynamic Active

• measurement



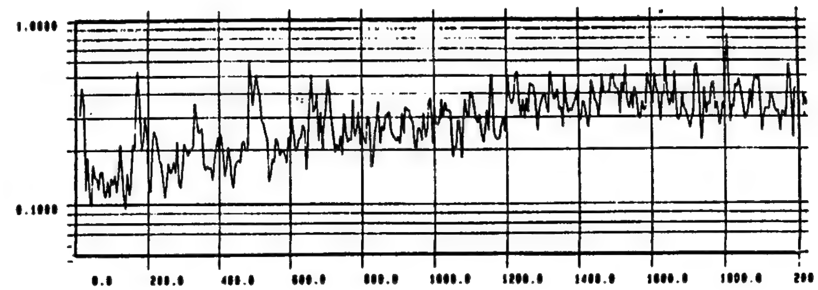
• prediction



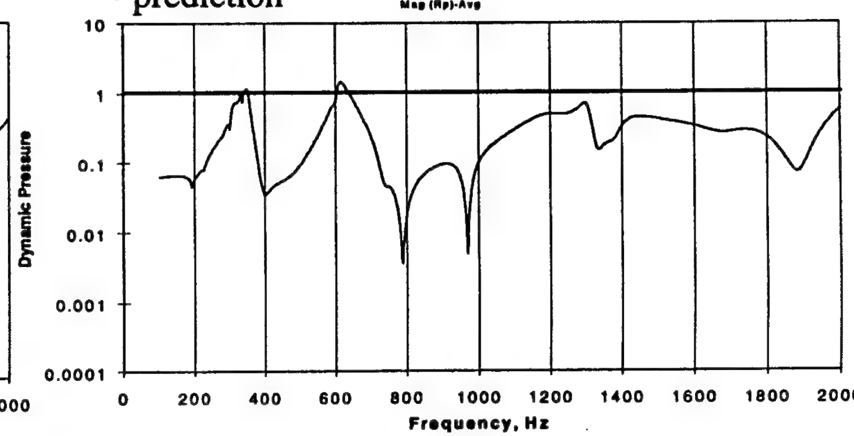
• Dynamic Inactive

• measurement

Case B:



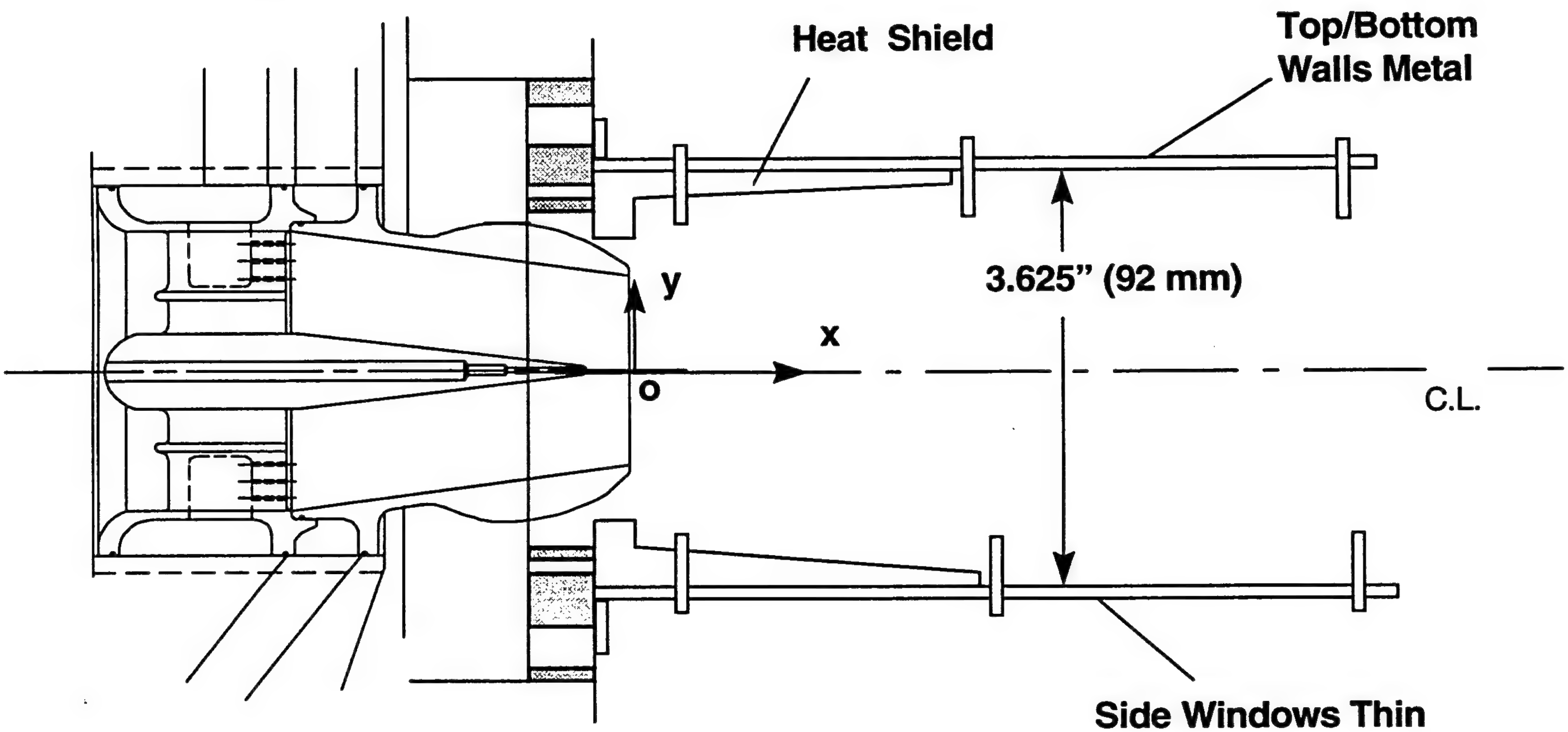
• prediction

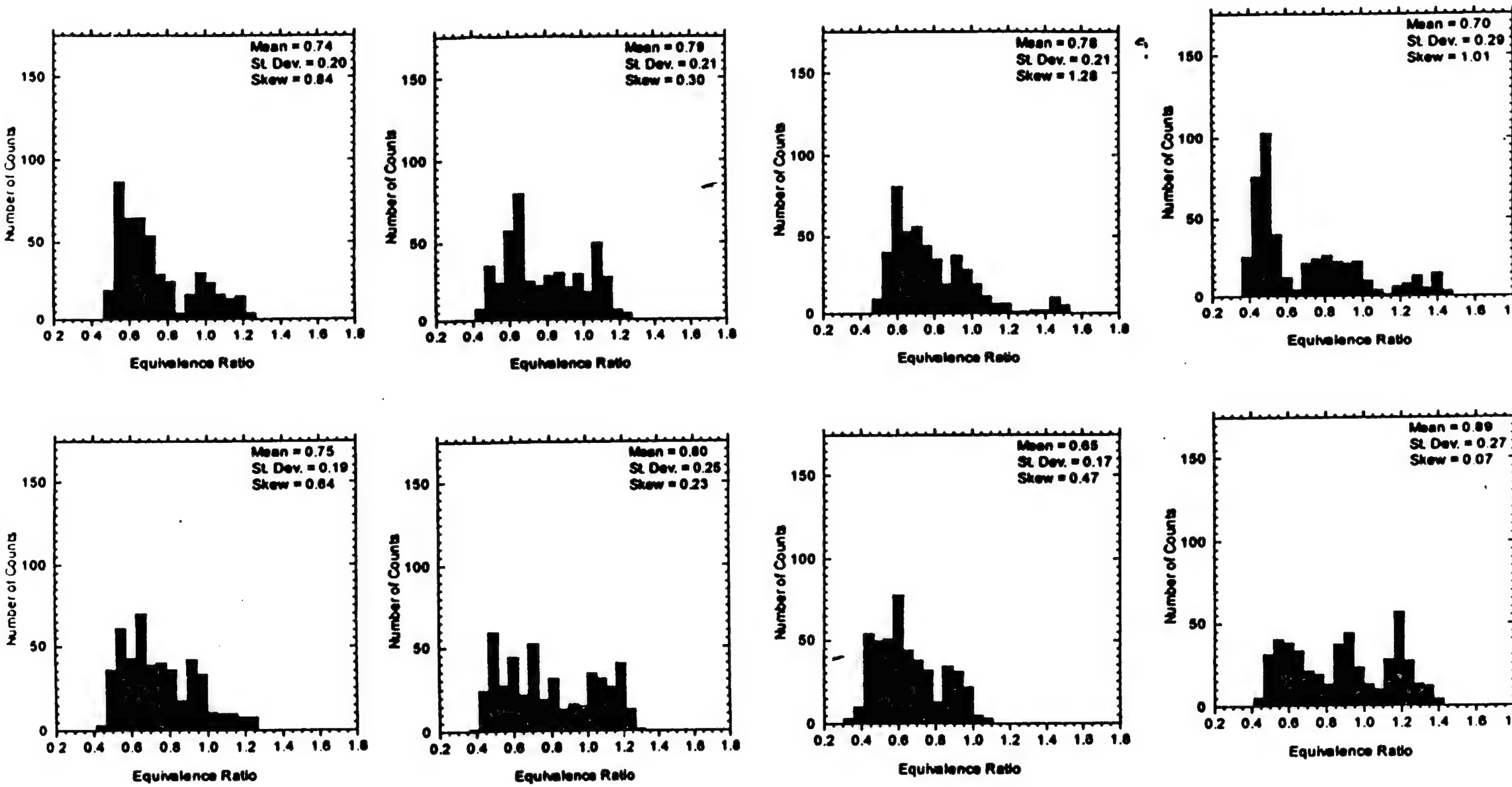


Fundamental Investigations for Next-Generation Design Tools

•Dynamic structure measurements at CR&D, Penn State, Univ of Illinois, UCI etc

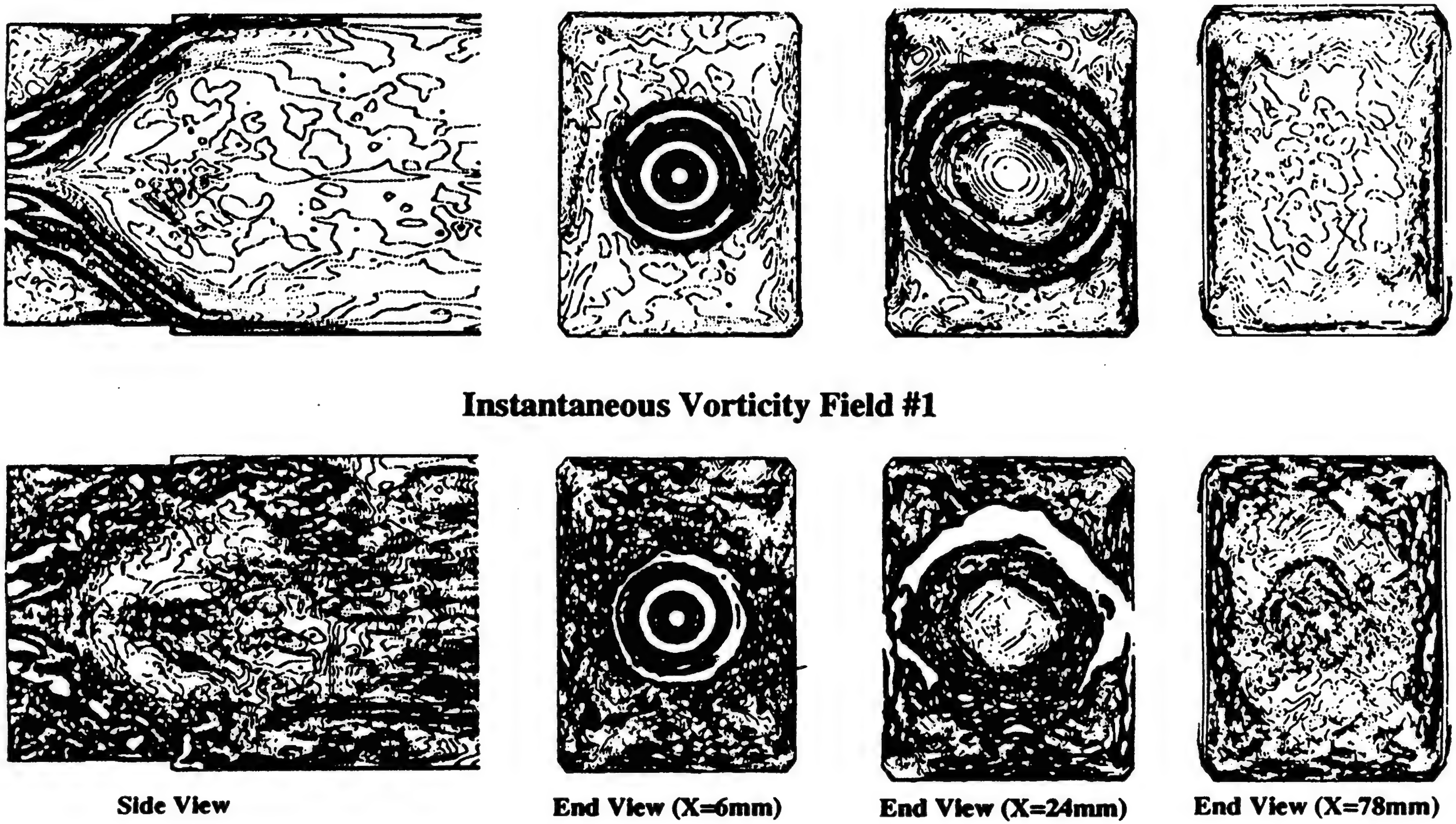
•Chen's Scalar PDF w/ Reduced Kinetics (approx 10 species), Large Eddy Simulation at Georgia Tech





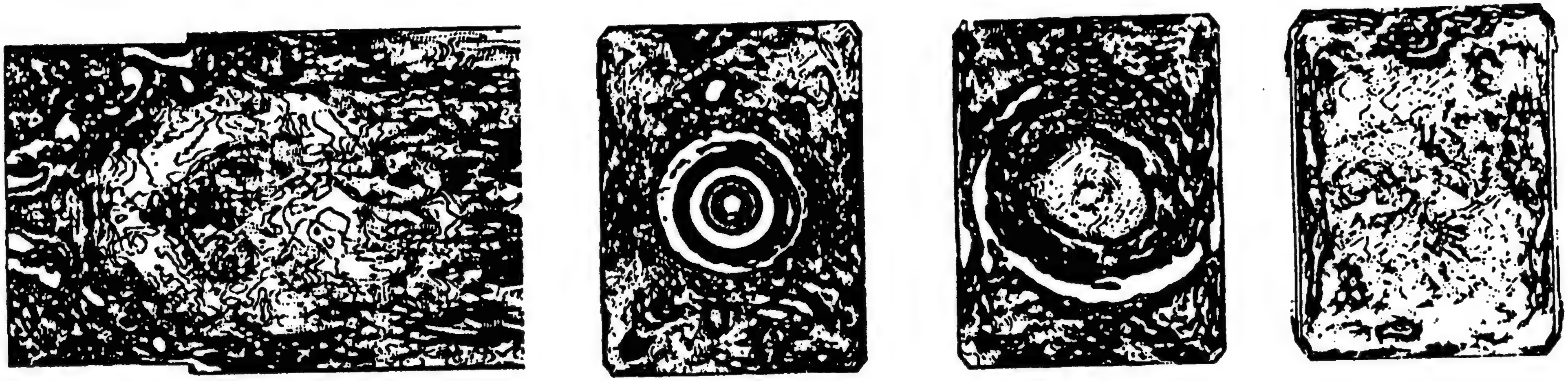
Measured local PDF's at selected points of a generic DLE mixer exit plane by Peters et al.

Time Averaged Vorticity Field

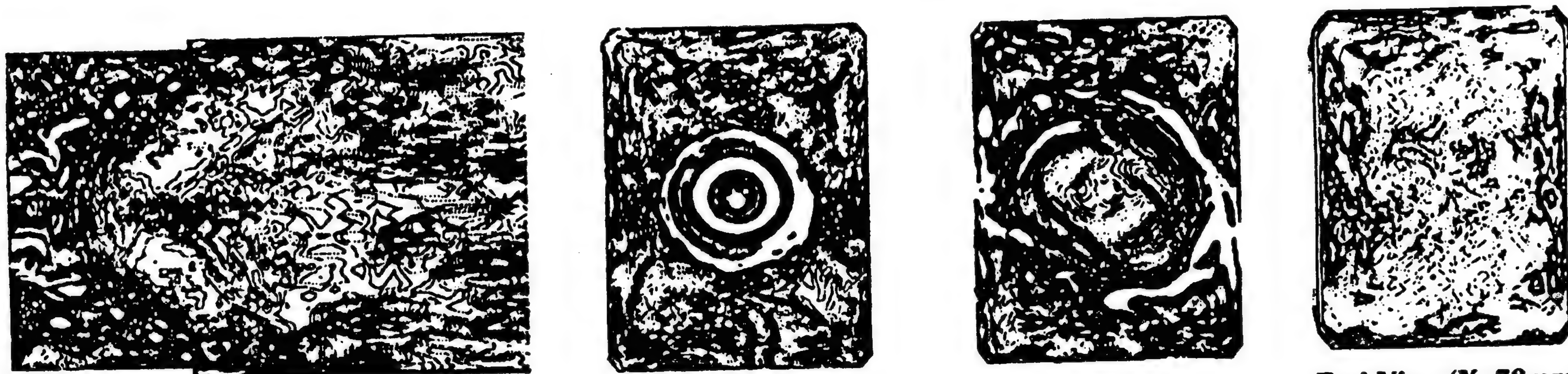


Time averaged and instantaneous Large Eddy Simulation (vorticity field) for the reacting DLE mixer by Menon

Instantaneous Vorticity Field #2

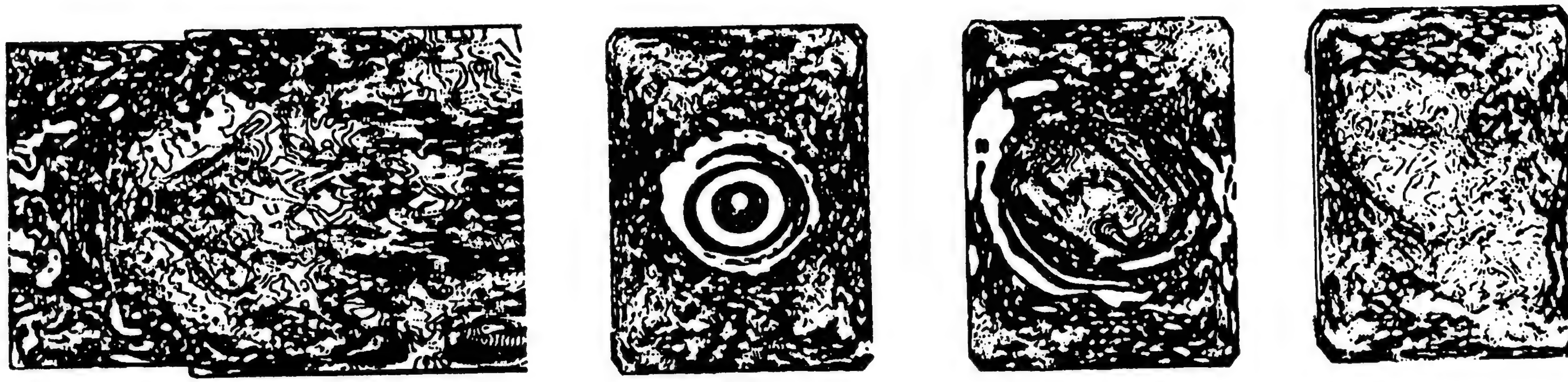


Instantaneous Vorticity Field #3

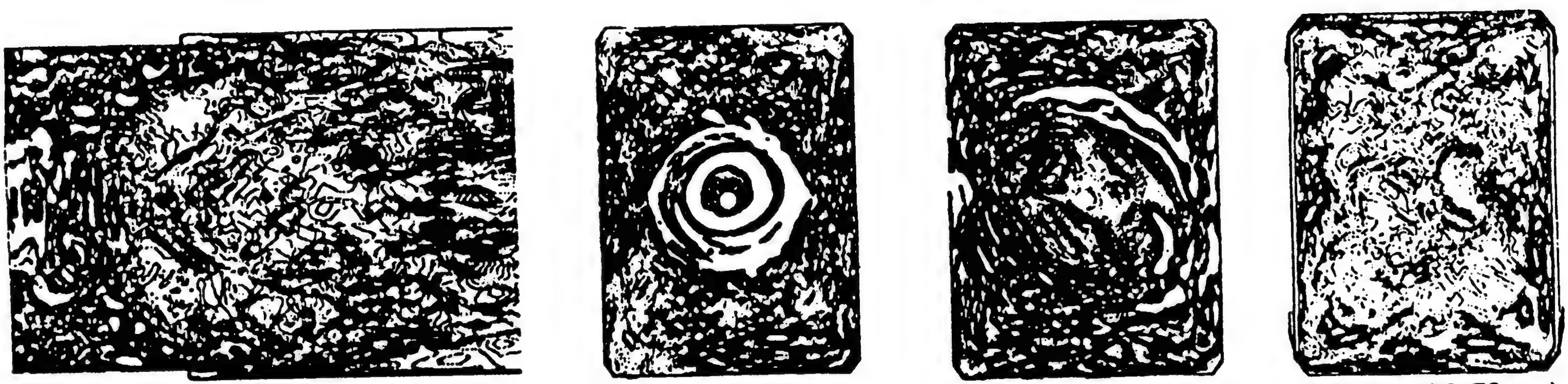


Instantaneous Large Eddy Simulation (vorticity field) for the reacting DLE mixer by Menon

Instantaneous Vorticity Field #4



Instantaneous Vorticity Field #5



Instantaneous Large Eddy Simulation (vorticity field) for the reacting DLE mixer by Menon

National Aeronautics and Space Administration
Lewis Research Center

REVOLUTIONARY COMBUSTOR FRONT-END DESIGN CONCEPT

Workshop on the "Needs and Technologies for Future Gas Turbines"
Georgia Institute of Technology
Daniel E. Sokolowski
June 15, 1998

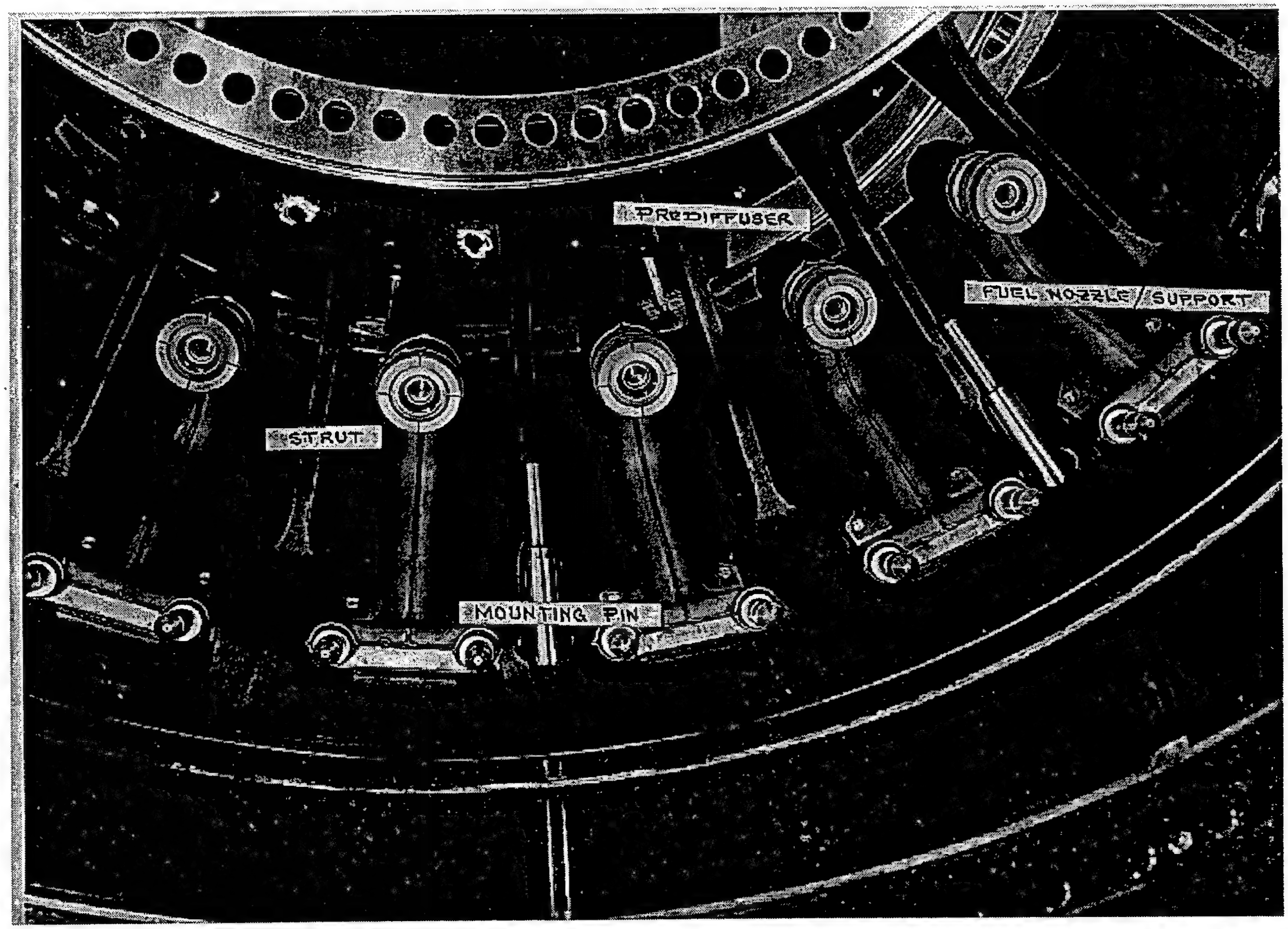
PRESENTATION

- **Gas Turbine Combustor**
  - **Current Design Paradigm**
  - **Revolutionary Front-End Design Concept**

- **Revolutionary Combustor Front-End Design Concept**
  - **New Paradigm**
  - **Full Annular - Sector Section Design**
  - **Concept Details**
  - **Active Control Concept**
  - **Unique Features and Benefits**
  - **Development**
  - **Chronology**

Gas Turbine Combustor

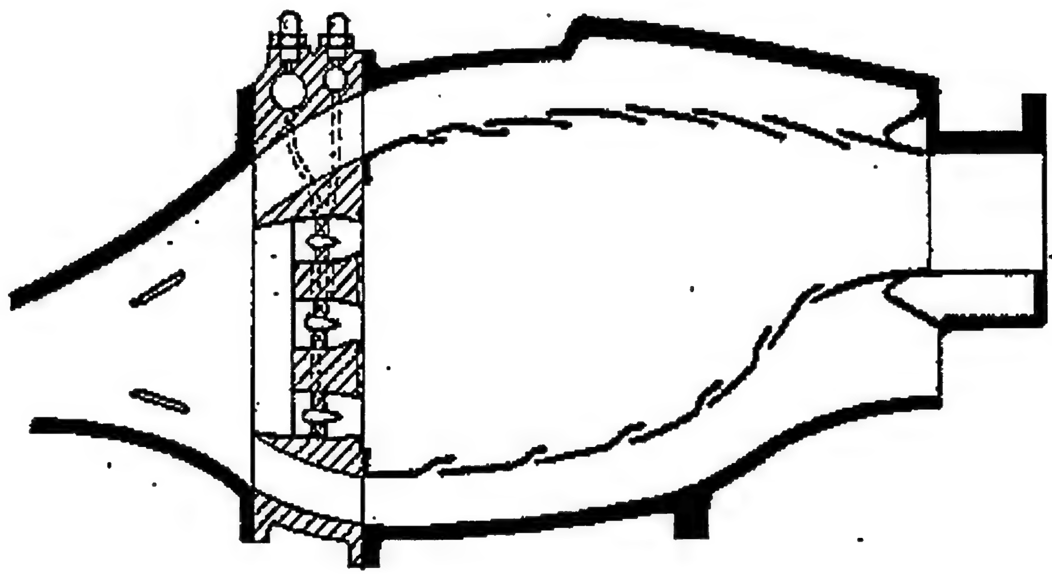
CURRENT DESIGN PARADIGM



Gas Turbine Combustor

REVOLUTIONARY FRONT-END DESIGN CONCEPT

...featuring an *Integrated Design* with *Laminated* Fabrication

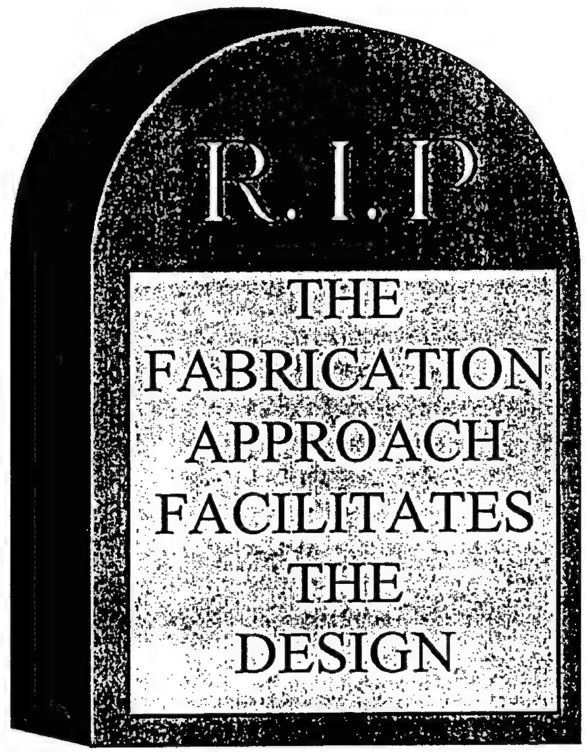


Front-end hardware items *integrated* into one unit:

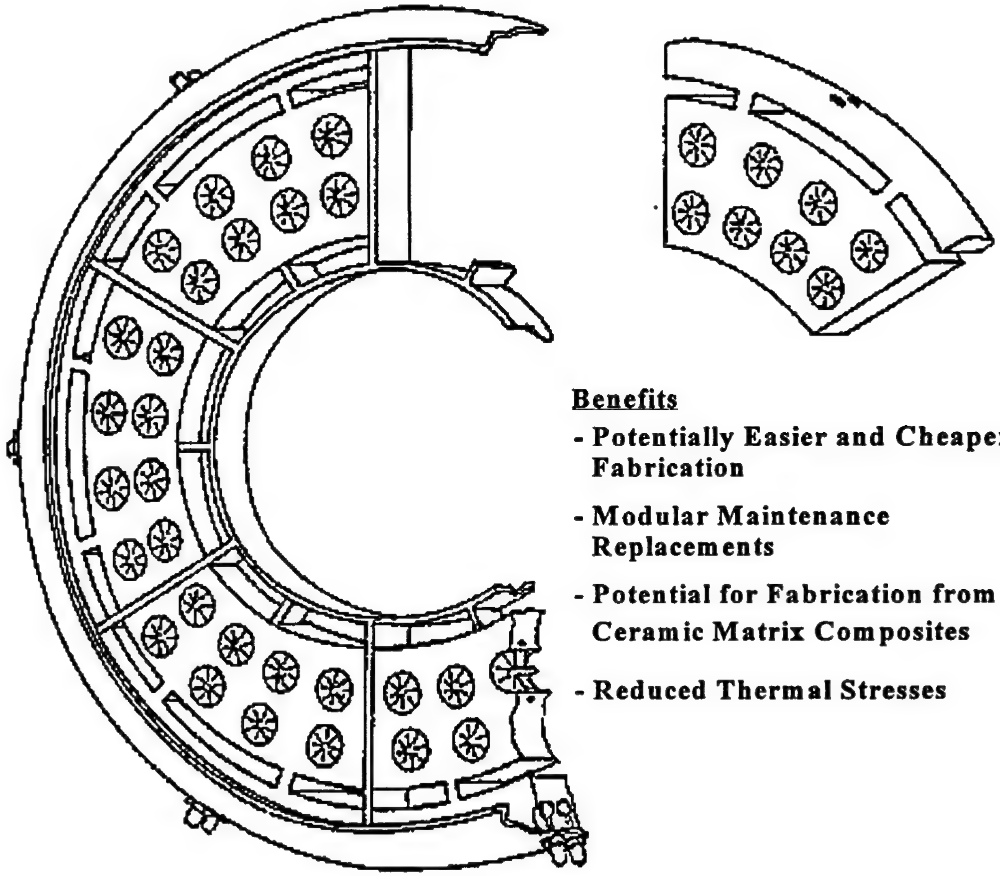
(1) Fuel Injector Support Assemblies and Heat Shielding
(2) Fuel Injectors
(3) Fuel Manifolds
(4) Potential for Fuel Control Mini-Valves
(5) Pre-Diffuser
(6) Case Struts & Mount Pins
(7) Hood
(8) Bulkhead

NEW PARADIGM

Revolutionary...**I**nnovative...**P**aradigm-breaking



Revolutionary Combustor Front-End Design Concept
FULL ANNULAR - SECTOR SECTION DESIGN

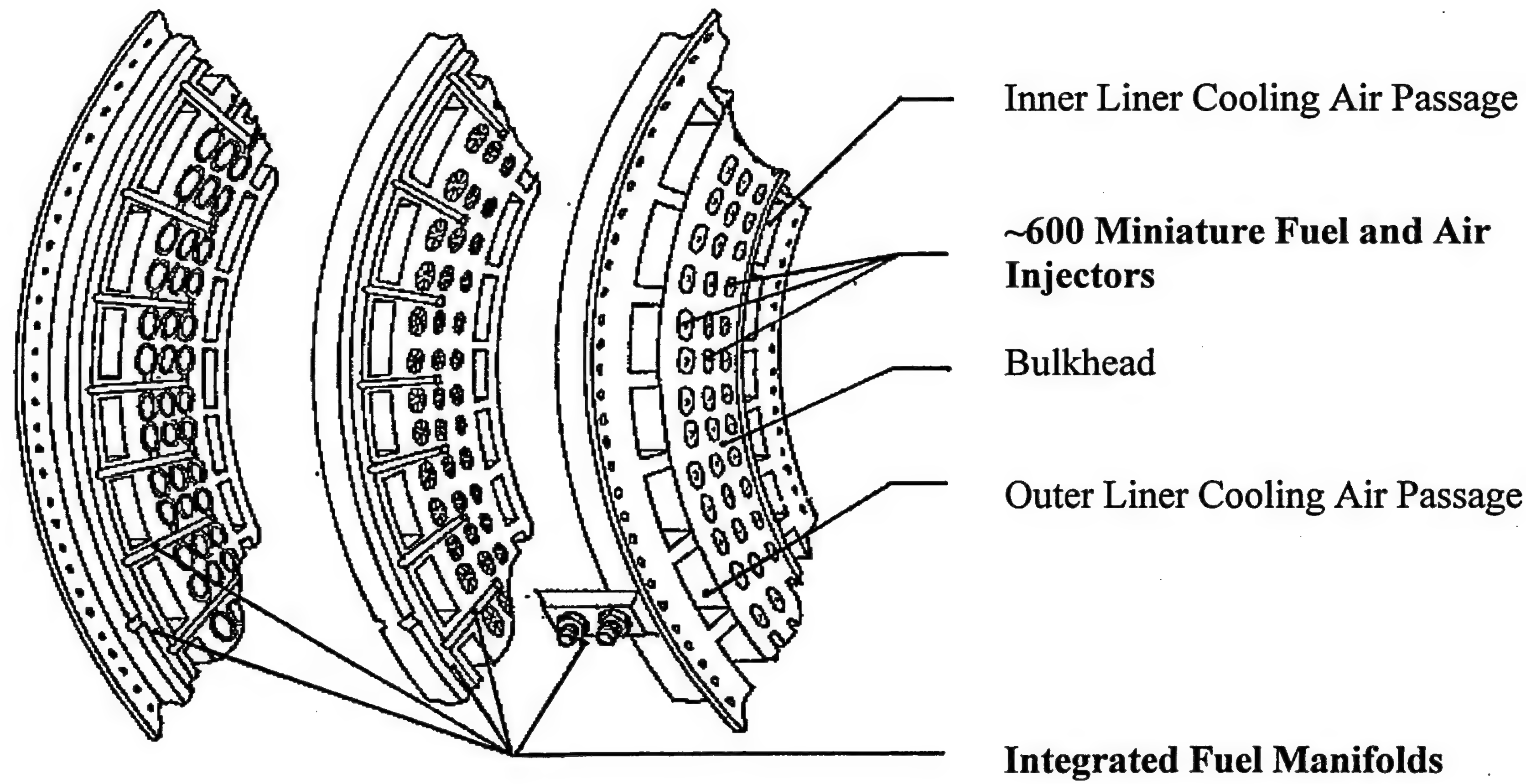


Benefits

- Potentially Easier and Cheaper Fabrication
- Modular Maintenance Replacements
- Potential for Fabrication from Ceramic Matrix Composites
- Reduced Thermal Stresses

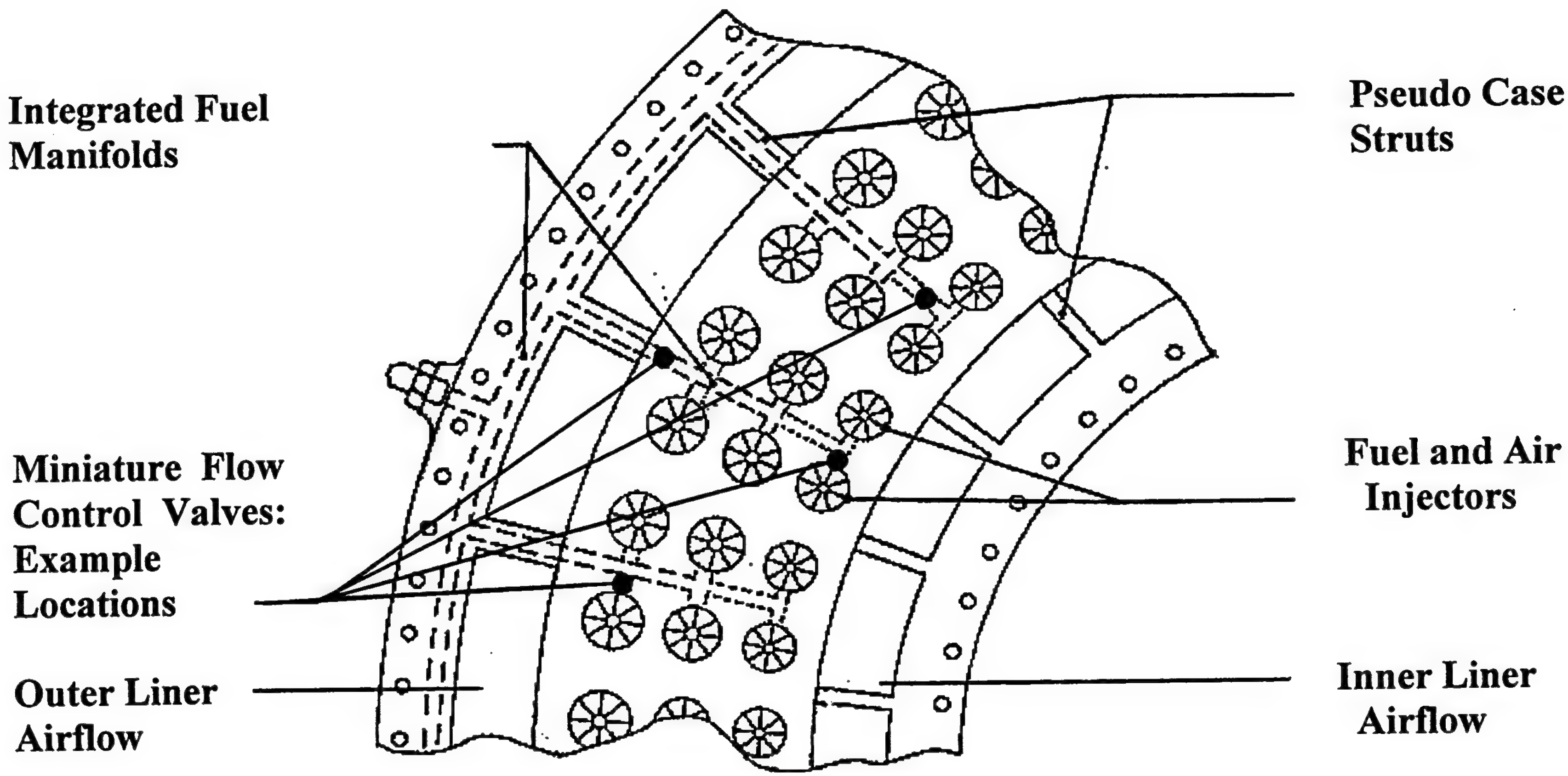
Revolutionary Combustor Front-End Design Concept

CONCEPT DETAILS



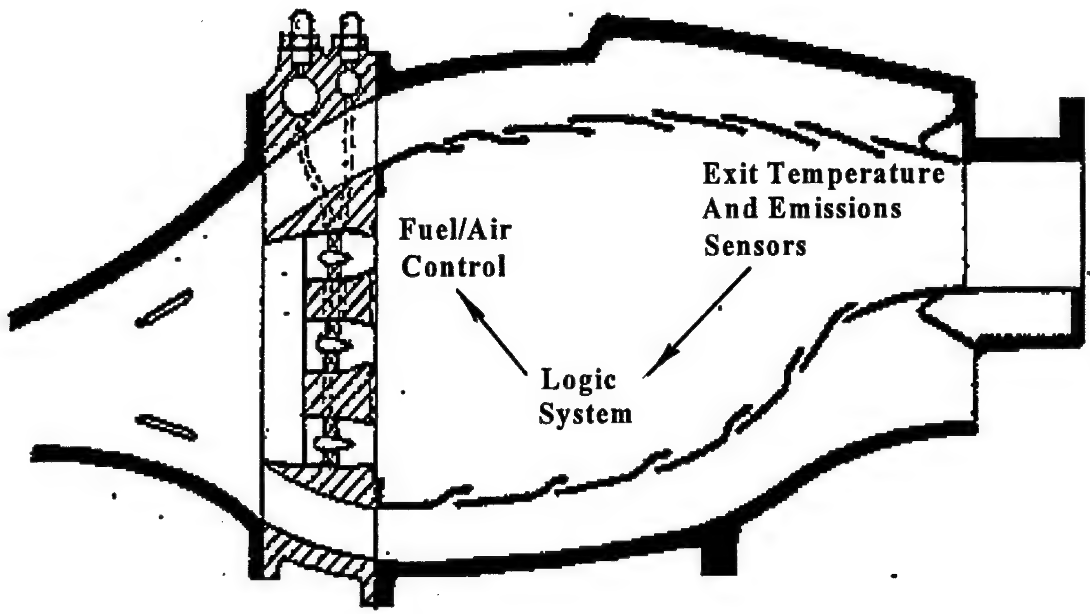
MicroElectroMechanicalSystems (MEMS)

ACTIVE CONTROL CONCEPT: MEMS- Controlled Fuel/Air Manifolds



MicroElectroMechanicalSystems (MEMS)

ACTIVE CONTROL CONCEPT: Sensors and Flow Control



Revolutionary Combustor Front-End Design Concept
UNIQUE FEATURES and BENEFITS

Features	Benefits
Stacked and Bonded Plates	**Higher-Temperature Operation** ▸ **Alloys** ▸ ***Structural Ceramics***
High-Density Fuel and Air Injection Points	**Improved Spatial Distribution** ▸ ***Reduced Emissions*** ▸ ***Increased Hardware Life***
Integrated Fuel and Air Manifolds	**Individual Injector Control** ▸ ***Reduced Emissions*** ▸ ***Increased Hardware Life*** **Improved Safety** **Reduced Throttle Response Time**

Revolutionary Combustor Front-End Design Concept
DEVELOPMENT

- **FABRICATION**
  - Rocket-based "Platelets" technology at Aerojet
    - Alloys since 1960s
    - Structural ceramics in 1980s
  - Gas turbine engine "Lamilloy" technology at Allison
- **CONCEPT DESIGN**
  - NASA LeRC study of PW2037 combustor
  - NASA LeRC experimental investigation with LDI (Aerojet)
  - Parker-Hannifin microlaminate injectors (silicon materials)
  - WPAFB/AFRL Trapped Vortex Combustor
    - IHPTET Phase III combustor

Revolutionary Combustor Front-End Design Concept

CHRONOLOGY

10-81	Concept conceived
12-81	Concept informally discussed with P&W
02-82	Completed internal NASA document which described concept
04-83	Formally presented concept to P&W combustion group
06-86	Initiated discussions with Parker Hannifin
11-86	Initiated an internal Lewis study with P&W cooperation
03-94	Contacted by Aerojet for application to HSCT
06-94	Initiated advocacy of concept to broad aeropropulsion community
06-95	Invited to apply concept to IHPTET
07-95	Expanded concept to include MEMS-based active control
11-97	Sent concept to NRC in response to NASA "Three Pillars" vision
04-98	Invited by Georgia Tech to present concept at workshop.

Active Control of Combustion Instabilities

Ben T. Zinn
Schools of Aerospace and Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150

Workshop on

Goals and Technologies for Tomorrow's Gas Turbines

Atlanta, Georgia
June 15-16, 1998

Acknowledgement

Support of AFOSR, ARO and DOE and the assistance of numerous colleagues and students

Combustion Instabilities

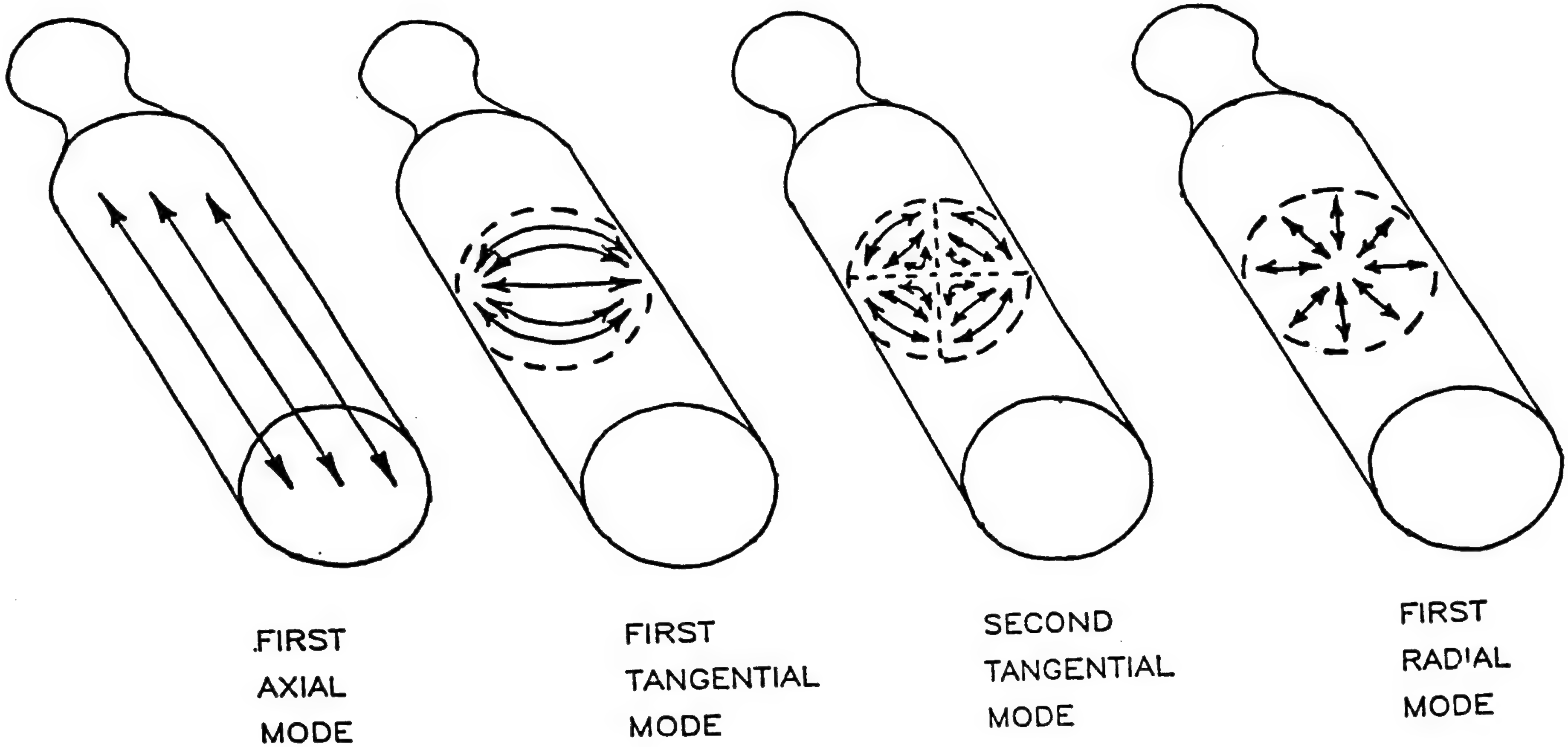
- Periodic oscillations of the combustor's **pressure**, velocity, temperature, and **reaction rate**

- Generally involves excitation of one or more acoustic modes of the combustor

- **Detrimental Effects:**
  - Excessive mechanical loads
  - Vibrations
  - Excessive heat transfer to walls or propellants

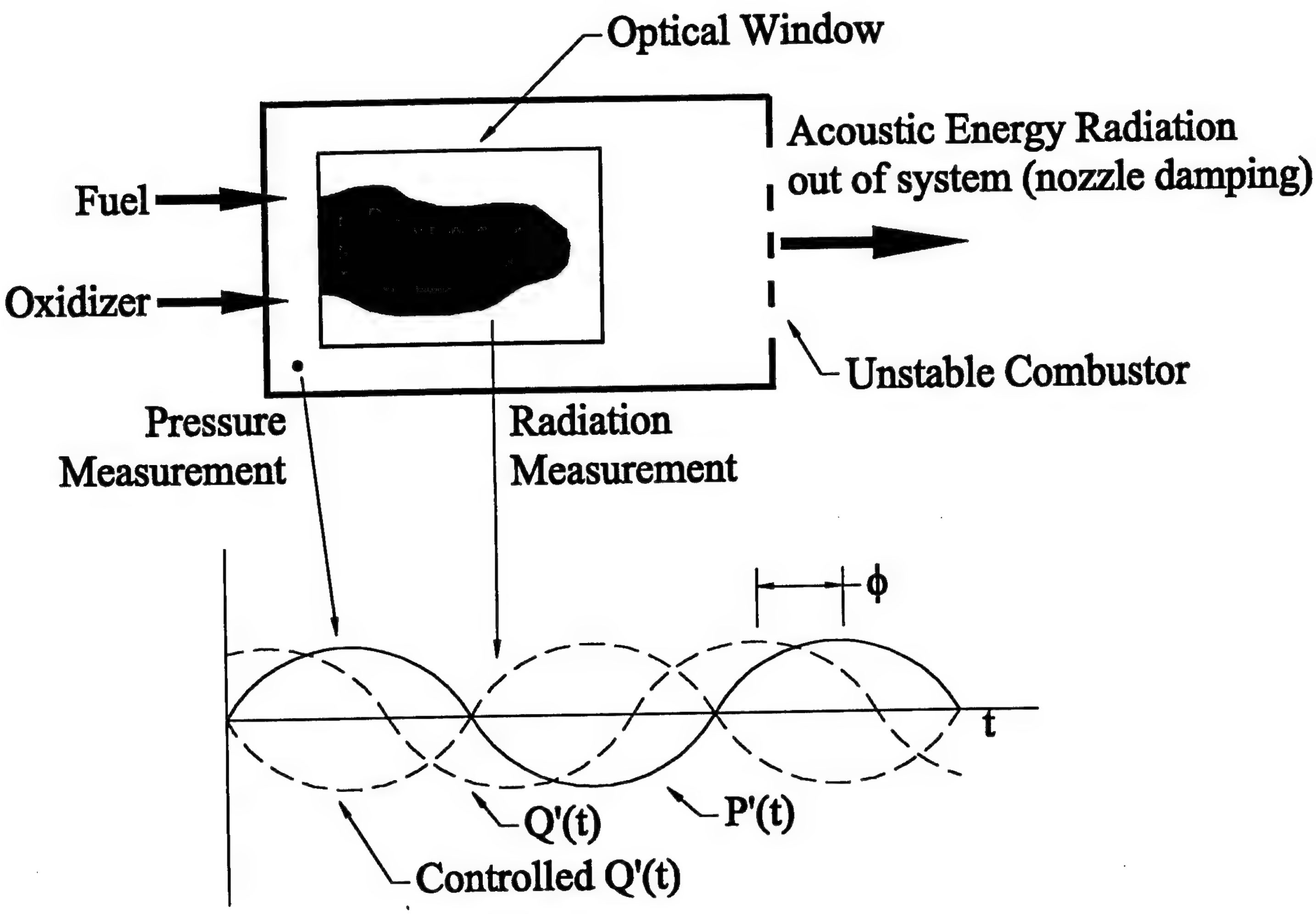
- **Passive Solution Approaches**
  - Trial and Error
  - Expensive
  - Lengthy, generally causing program delays
  - Not always effective

A REASONABLY PRICED, DEPENDABLE APPROACH FOR CONTROLLING COMBUSTION INSTABILITIES IS NEEDED!



Cavity modes: examples of standing acoustic modes in right circular cylinders.

Driving of Combustion Instabilities



$$G = \text{Combustion Process Driving} = \frac{1}{T}\int_0^T \int_{V_c} p'(t)Q'(t)dVdt;$$

$$G > 0 \text{ when } |\phi| < 90^\circ$$

$$D = \text{Combustor Damping} = \frac{1}{T}\int_0^T \int_{S_N} p'(t)u'(t)dSdt$$

$$+ \text{ viscous dissipation} + \ldots$$

Combustor is unstable when $G > D$ and vice versa

Ga. Tech's Active Control System's Objectives and Challenges

Objective: Develop an active control system (ACS) that can prevent the onset and/or damp rocket motor instabilities.

Characteristics of rocket instabilities and ACS needs:

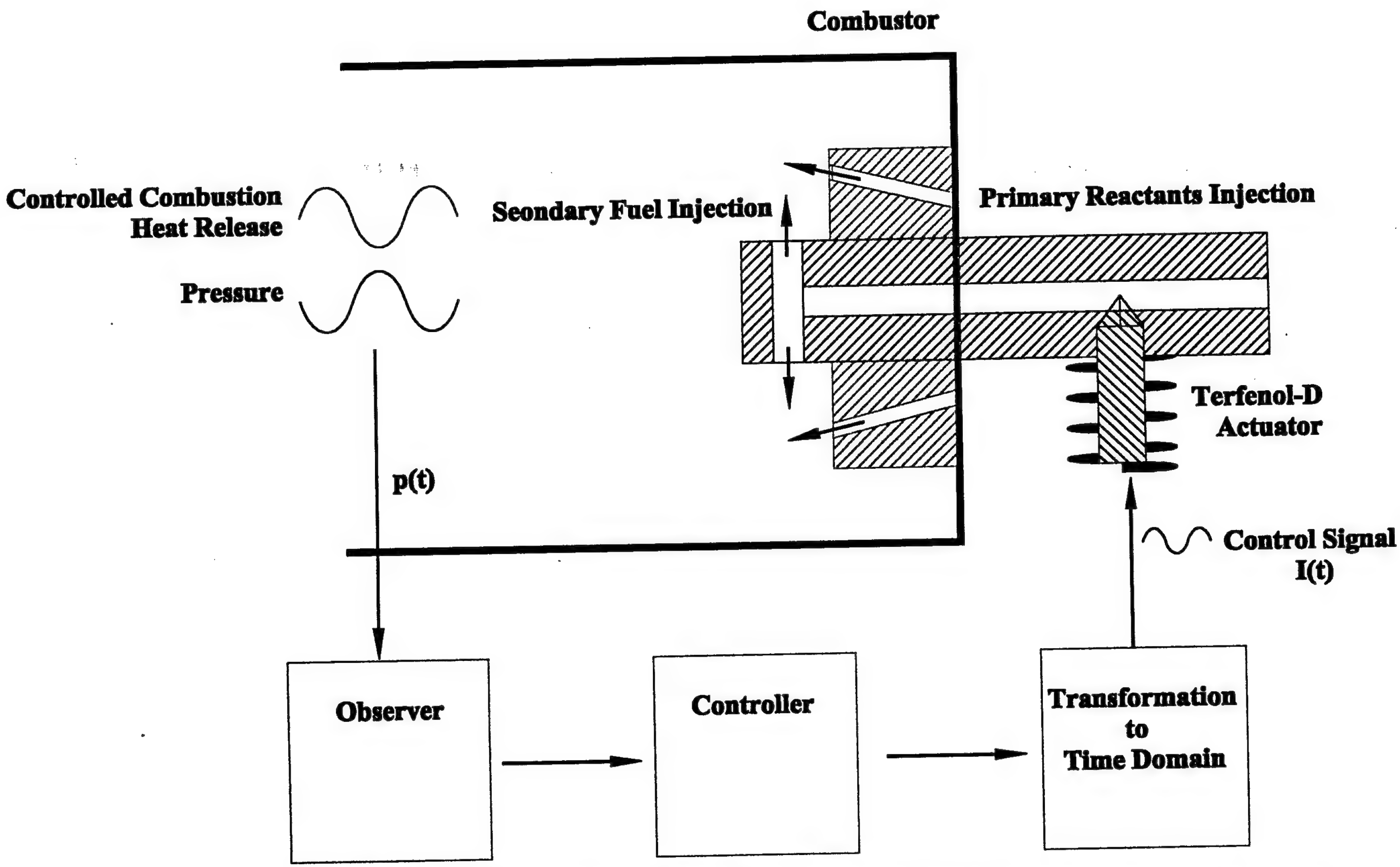
Problem		Needs
1. large amplitude	⇒	large actuation
2. multi-mode excitation	⇒	multi-mode controller
3. detrimental	⇒	rapid damping
4. time varying	⇒	"adaptive" & fast responding controller
5. high frequency	⇒	actuation over a wide frequency range

Basic Considerations

- The behavior of the system is described by oscillating modes with time varying frequencies, amplitudes and phases
- Generally, the characteristics of the unstable modes are not known a priori

Control Approach

- Real time identification of unstable modes in the frequency domain
- Amplify each mode separately
- Phase shift each mode separately so that the heat release produced by a secondary, oscillatory, fuel injection rate is 180 degrees out of phase with the mode's pressure oscillations (Rayleigh's criterion)
- Use the amplified and phase shifted modes to construct a control signal for the secondary fuel injector

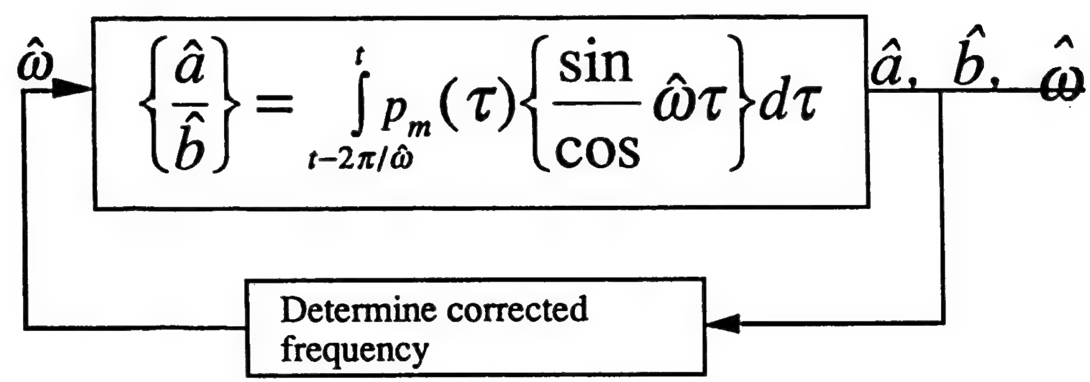


A schematic of Georgia Tech's active control system/approach

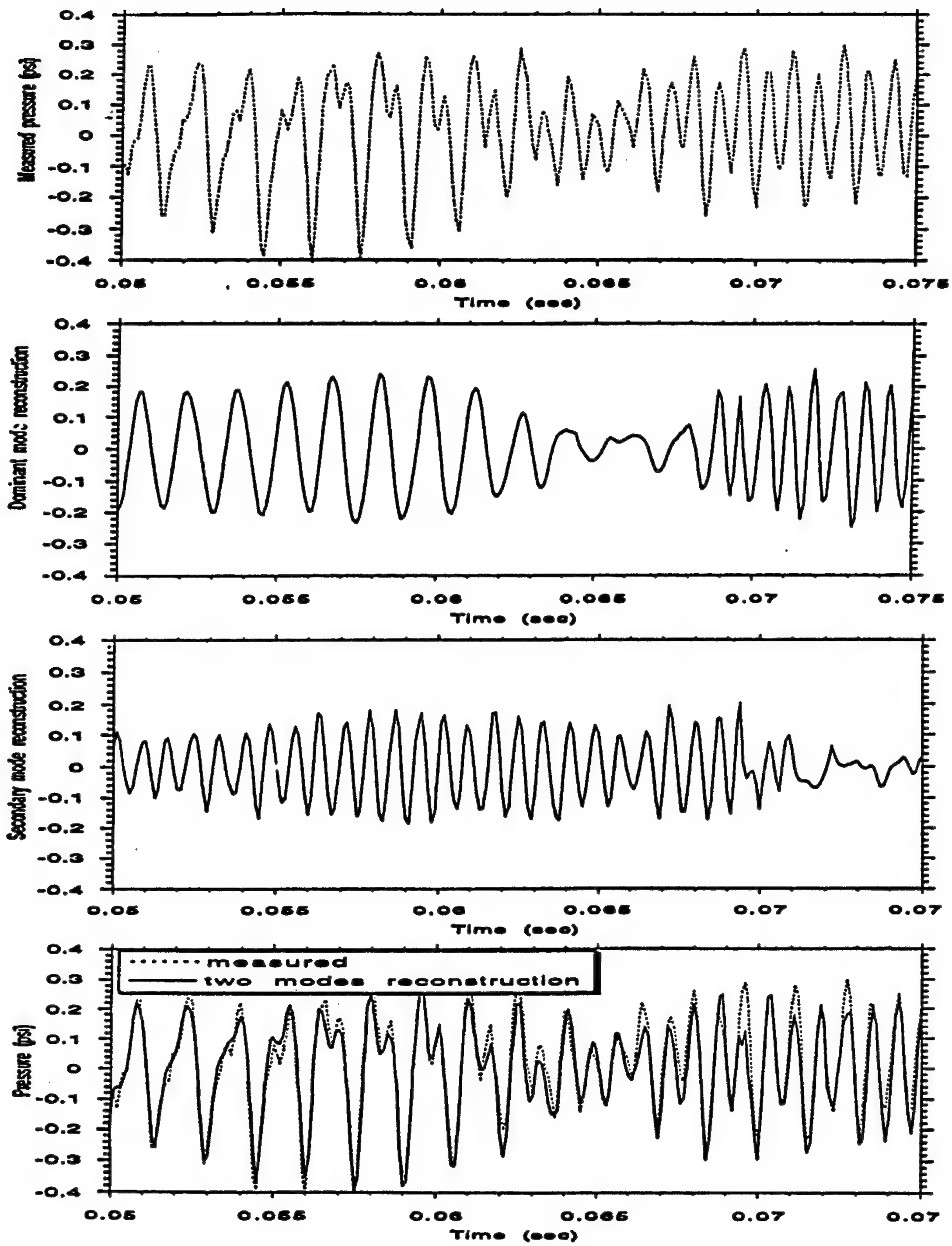
GEORGIA TECH'S OBSERVER

Measured Pressure p_m is expressed as: $p_m(t) = \sum_{n=1}^{N}[a_n \sin(\omega_n t) + b_n \cos(\omega_n t)]$

"Description" of observer algorithm

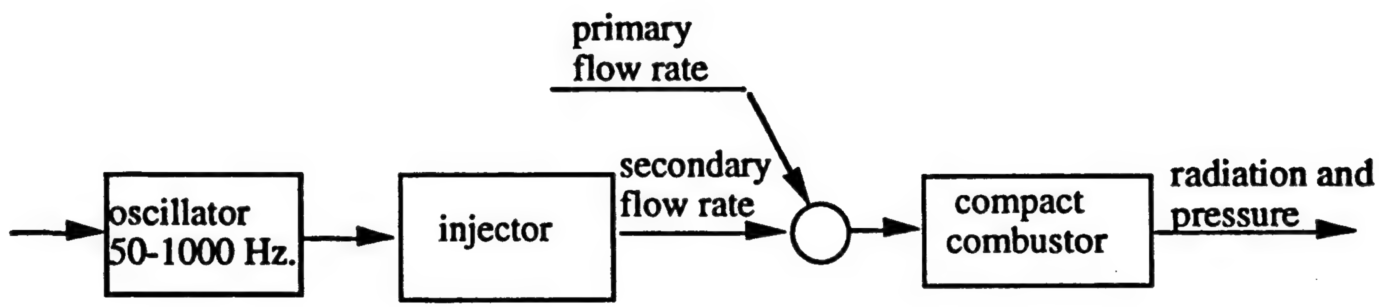


- Unstable modes' frequencies not know apriori
- Solution rapidly determines the dominant mode characteristics
- Procedure can be repeated to determine several unstable modes

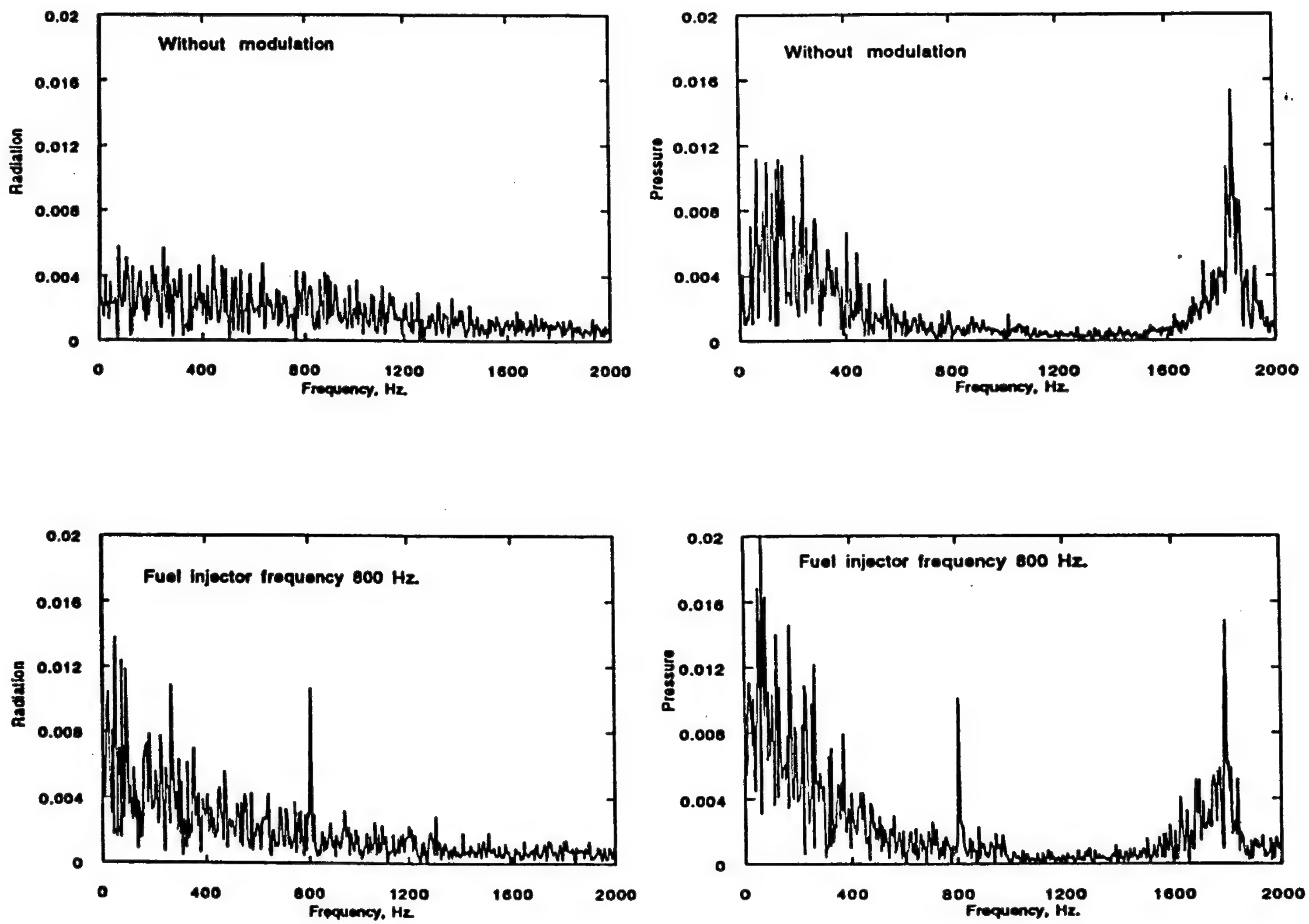


Example of real time observation of a transient instability in the Georgia Tech gas rocket

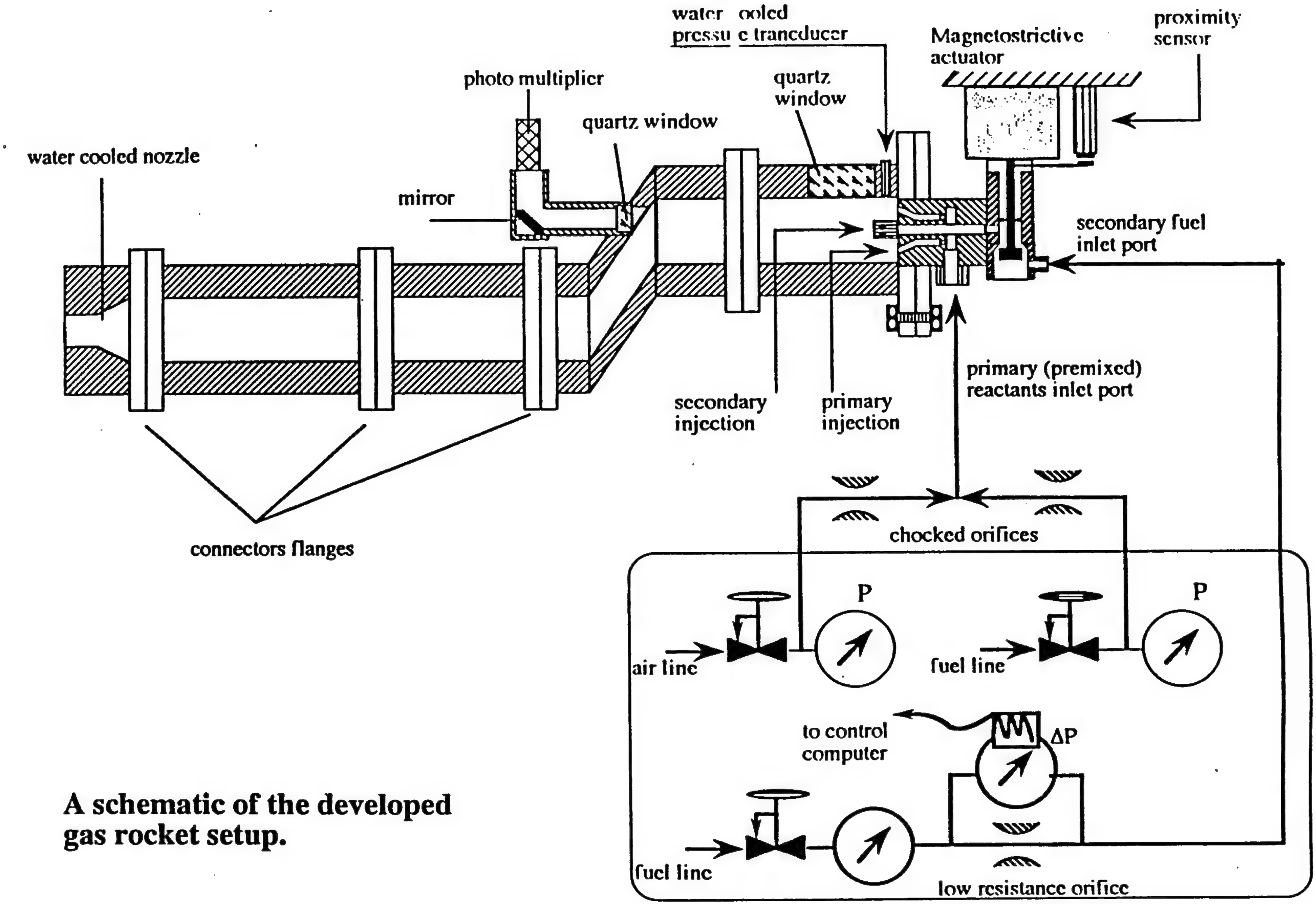
Georgia Tech's Setup for Controllability Evaluation



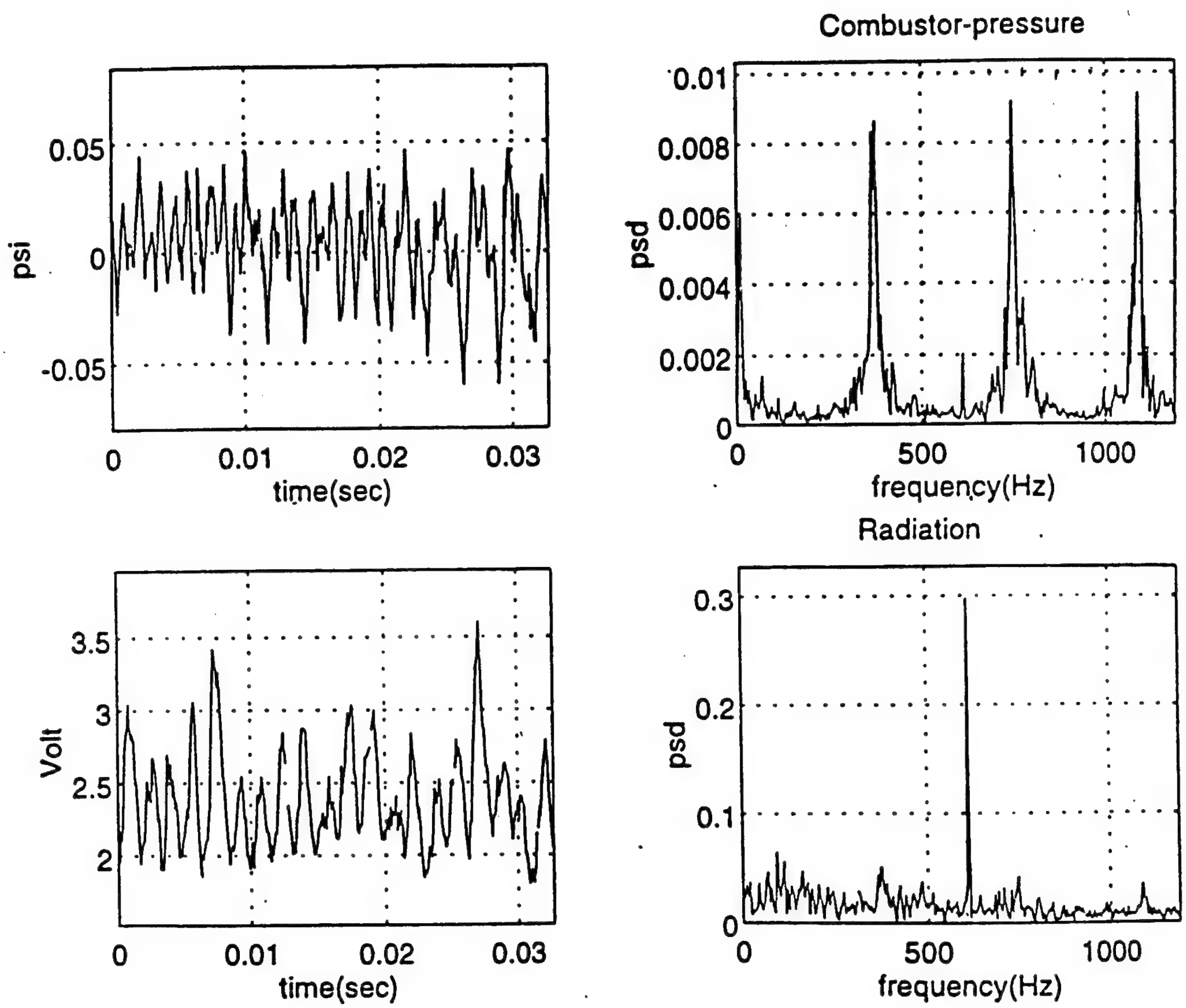
- The natural frequencies of the compact combustor > than 1600 Hz.
- Modulation of the secondary fuel injection rate at frequencies well below the first fundamental acoustic mode of the combustor



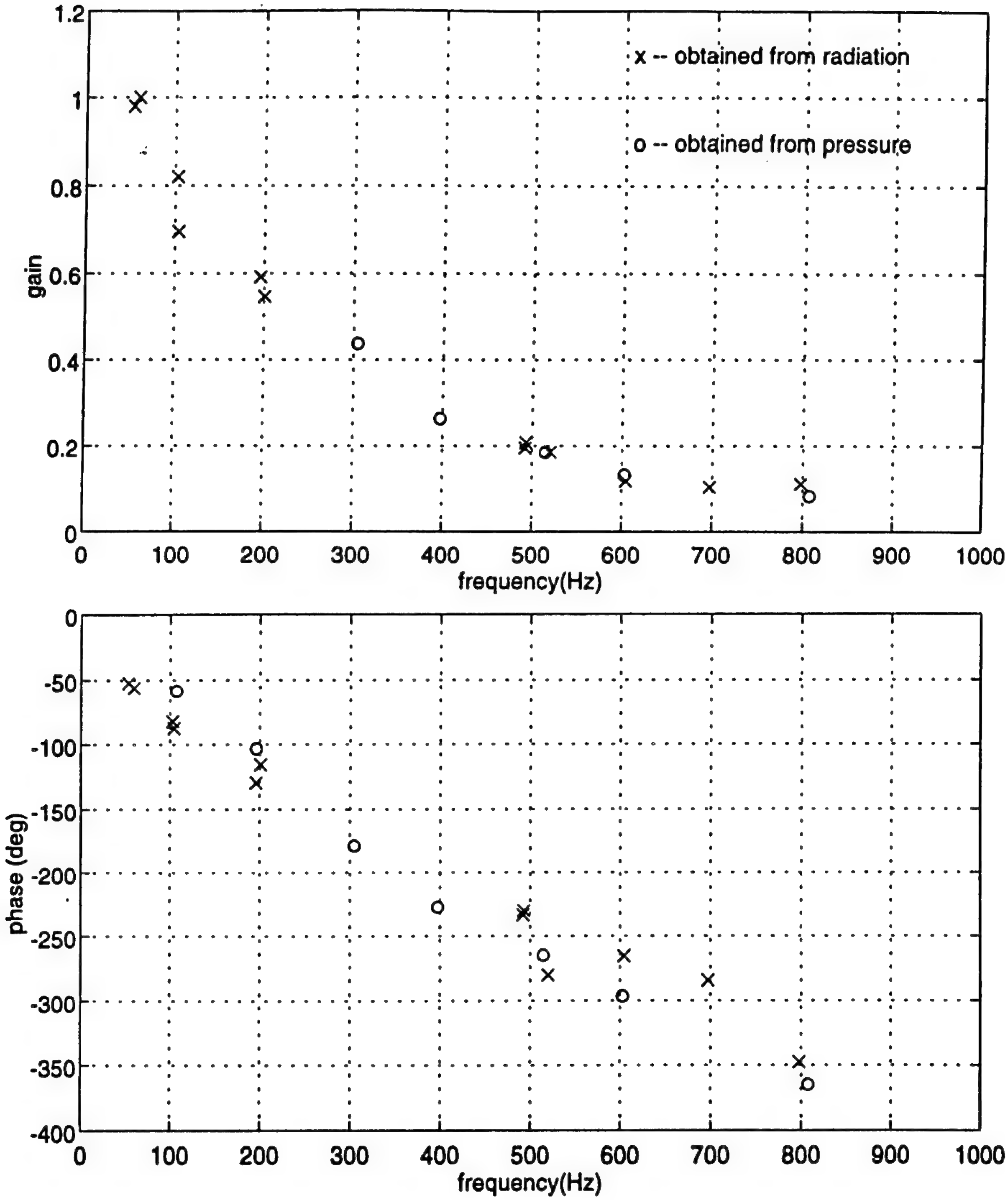
Radiation and pressure spectra with and without open loop driving at 800 Hz.



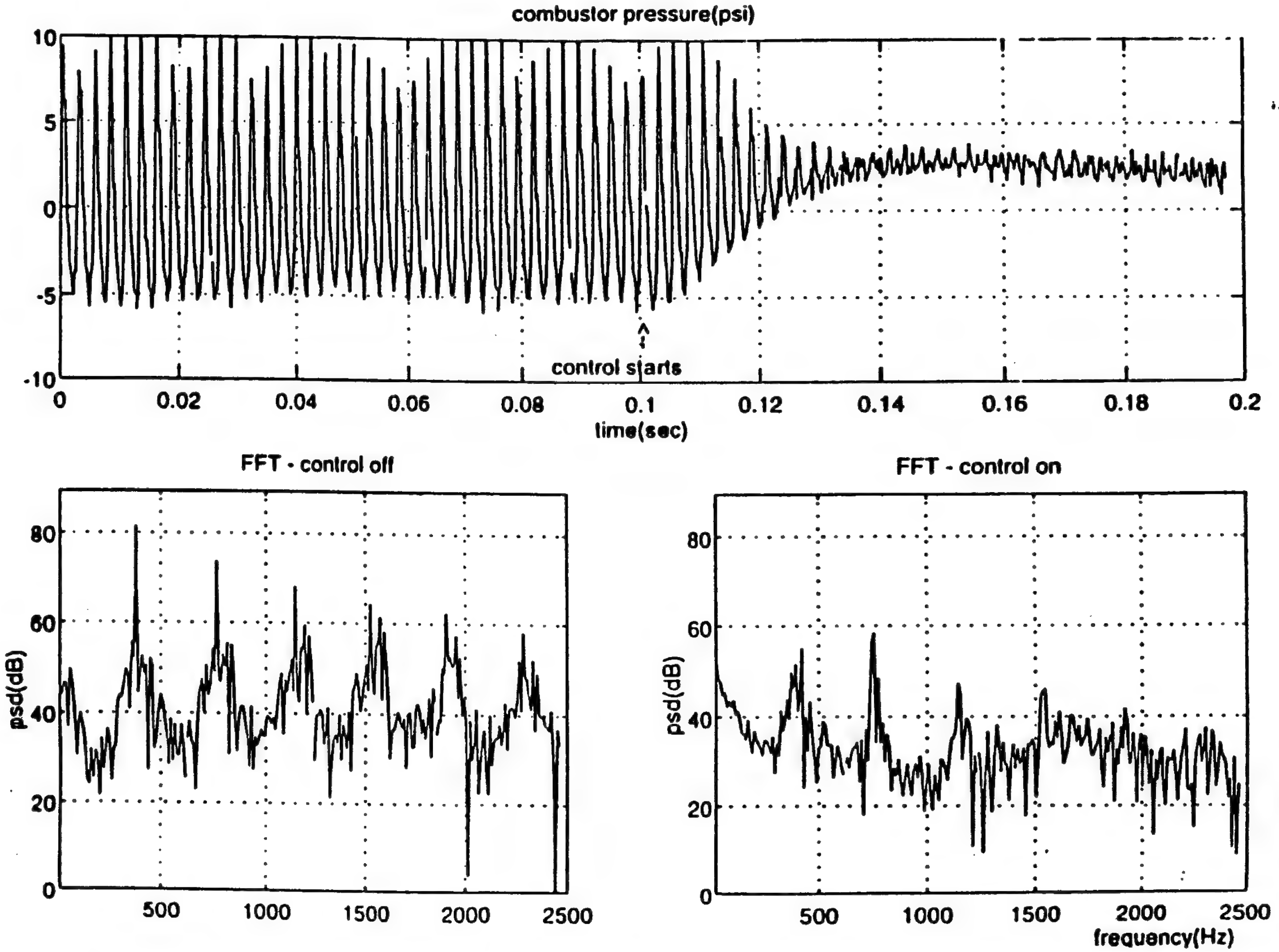
A schematic of the developed
gas rocket setup.



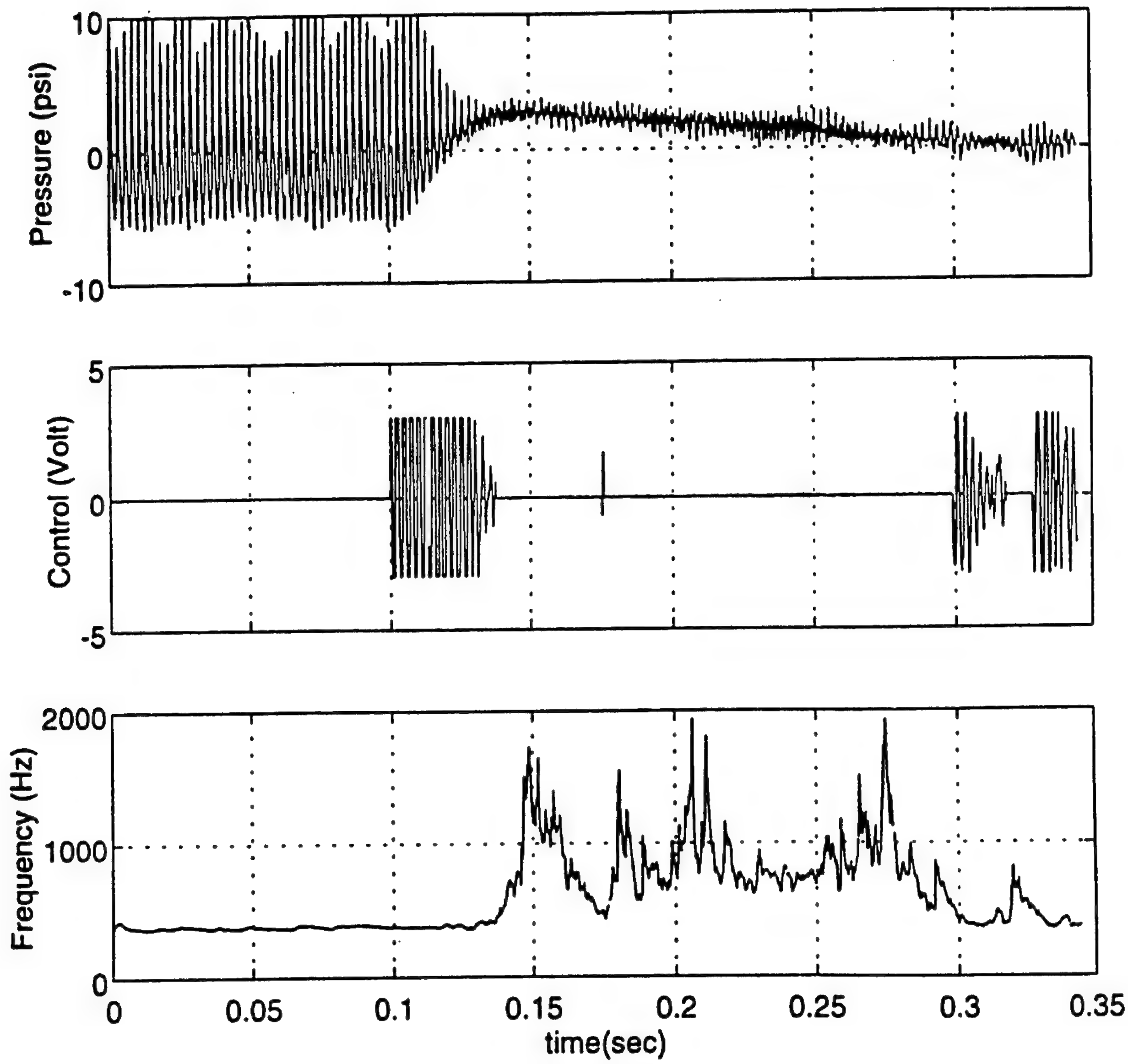
Time dependence and spectra of the combustor pressure and combustion region CH radicals radiation measured in an open loop experiment



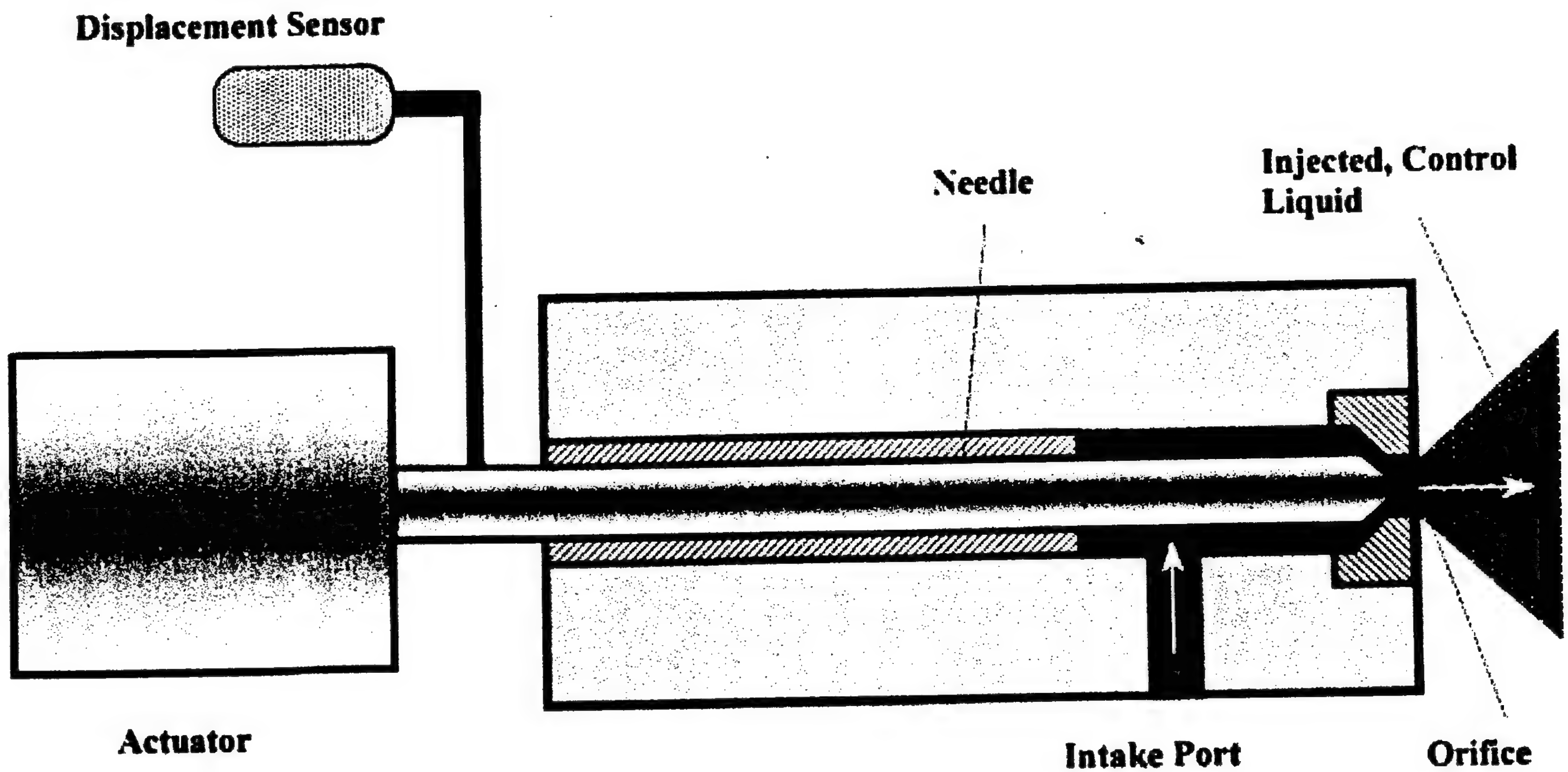
Comparisons of the frequency dependence of the heat release gain and phase obtained in two different open loop tests at Georgia Tech



Time dependence and frequency spectra of unstable combustor pressure oscillations before and after initiation of active control in the Georgia Tech gas rocket



Time dependence of the combustor pressure, control signal and observed frequency before and after initiation of closed loop active control in the Georgia Tech gas rocket



A Schematic of the Developed Liquid Injector Actuator

Not in Scale

SUMMARY AND TECHNOLOGY STATUS

- Feasibility of active control of combustion instabilities has been successfully demonstrated on small and large scale combustors
- Fuel modulation appears to be the control approach of choice
- Future applications of this active control technology to a wide range of combustors will require:
  - **optimization of the control system (e.g., reduction of the amount of secondary fuel required)**
  - **development of "fast" adaptive control systems**
  - **development of large scale fuel injector actuators that operate over a wide frequency range**
  - **demonstration that the actuator(s) and sensors can operate continuously and without failure over periods years**

ACTIVE COMBUSTION CONTROL USING PULSED FUEL INJECTION

Ken H. Yu

Propulsion Research Lab
Research & Technology Group
Naval Air Warfare Center
China Lake, CA

presented at the Active Control of Gas Turbine Workshop
June 15-16, 1998; Georgia Tech, Atlanta, GA

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NAVAL AIR WARFARE CENTER

ACKNOWLEDGMENT

- SPONSORS
  - ONR, SERDP, ILIR
- ACTIVE COMBUSTION CONTROL RESEARCH STAFF
  - DR. TIM PARR
  - DR. KLAUS SCHADOW
  - MR. BOB SMITH
  - MR. KEN WILSON
  - DR. KEN YU

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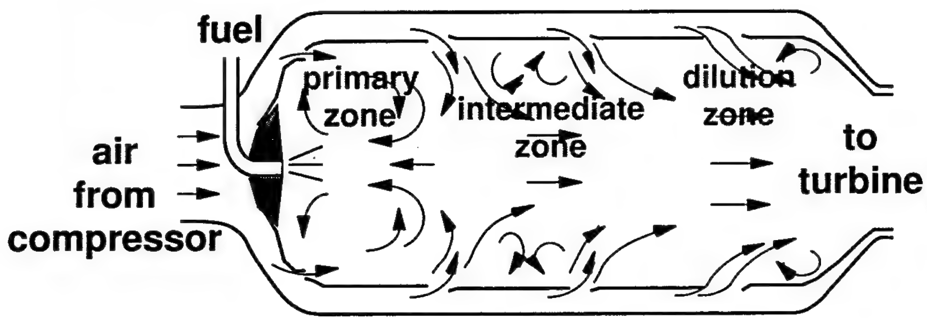
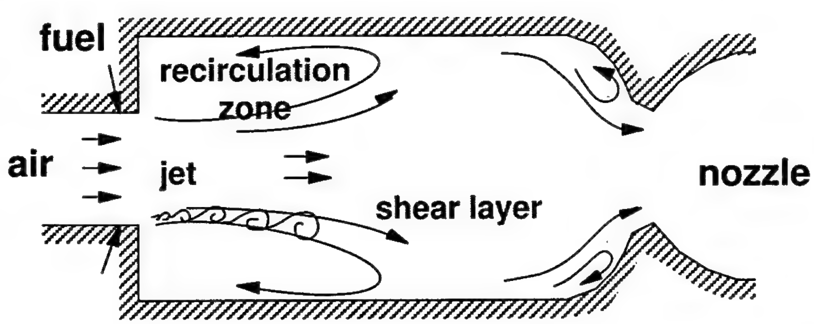
ACTIVE CONTROL OF FUEL-AIR MIXING

Gas Turbine



Dump Combustor



- **SHEAR FLOW DYNAMICS** are determined by interaction between fluid dynamic, chemical kinetic, and acoustic processes.

- **PULSED FUEL INJECTION** provides a practical means to control the interaction between the various processes.

- **UNDERSTANDING OF BASIC COMBUSTION AND MIXING PROCESSES** is critical for proper application of active control.

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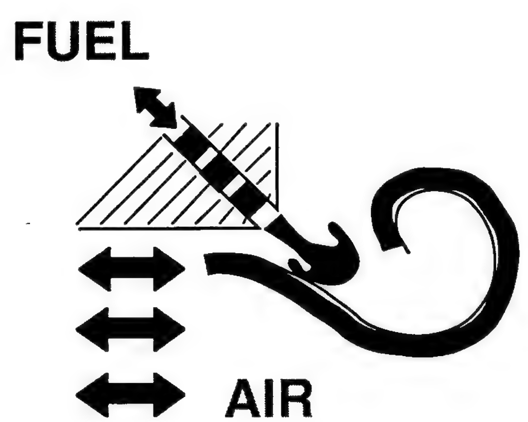
CONTROLLED FUEL-AIR MIXING



EFFICIENCY

- ENHANCED TURBULENCE
- RESIDENCE TIME
- LOCAL MIXTURE RATIO

INSTABILITY

- PERIODIC HEAT RELEASE
- RAYLEIGH'S CRITERION

LIQUID FUEL

- FUEL ATOMIZATION
- FUEL DROPLET DISPERSION
- PERIODIC VORTEX-DROPLET INTERACTION

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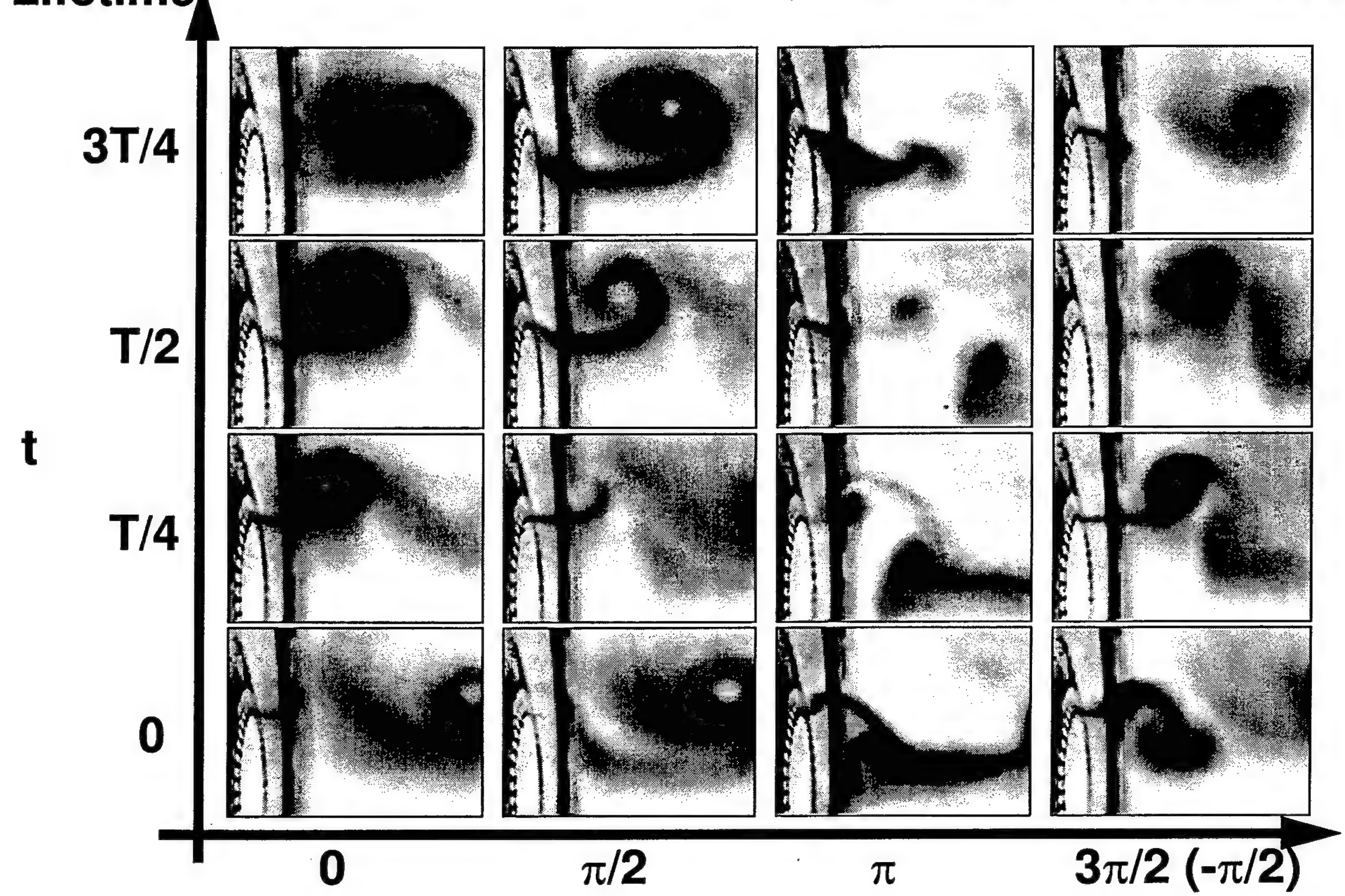
Planar Mie-scattering Images of Pulsed Fuel Injection into Air Vortex

- ❑ Phase-Locked Average of Smoke-Seeded Fuel Flow (10 instantaneous images averaged)

Vortex Lifetime



f_{ext} = 180 Hz (fD/U = 0.5)

Relative Phase (θ_{air}-θ_{fuel})

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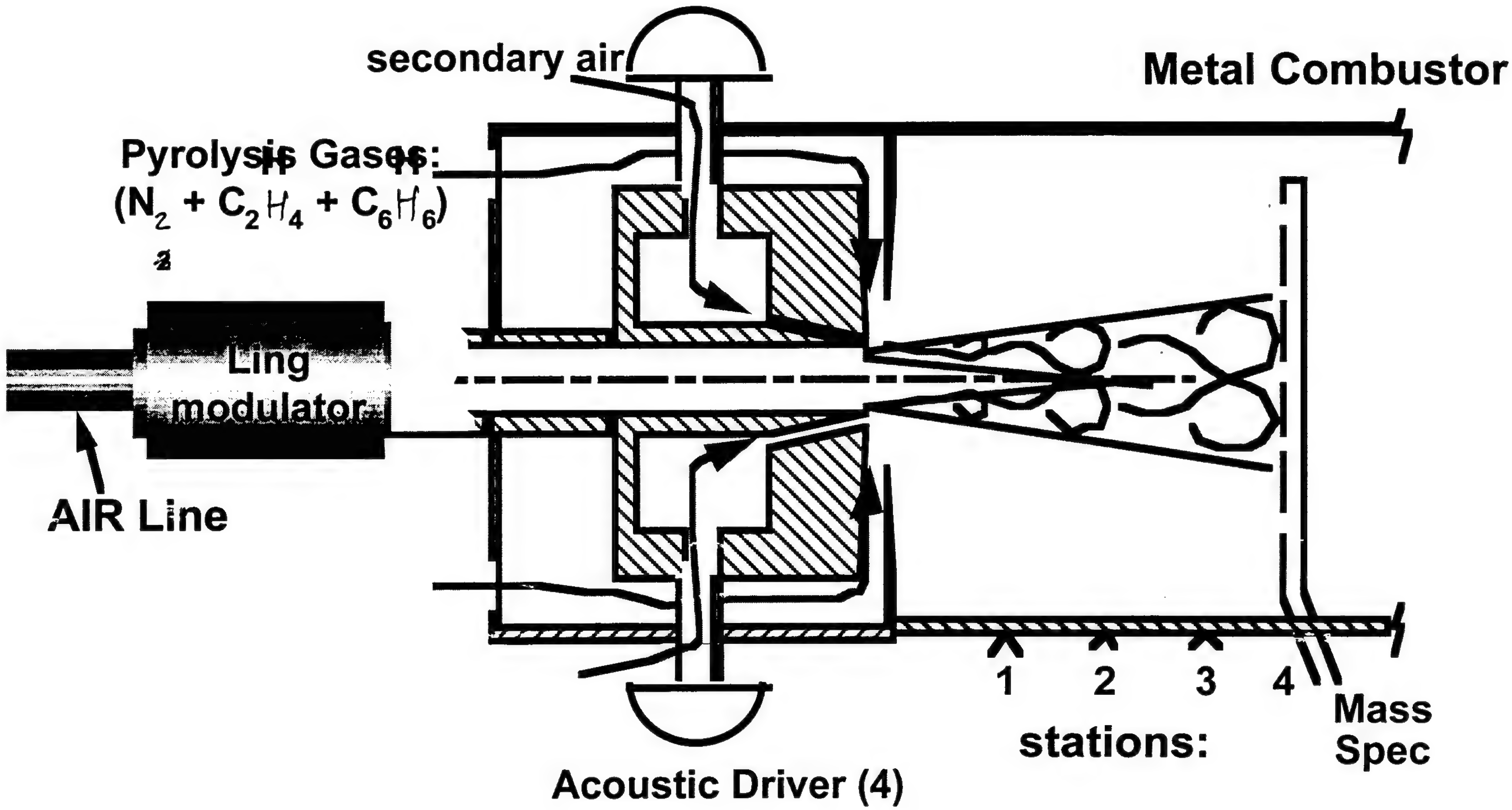
Gaseous Fueled Dump Combustor Set-Up



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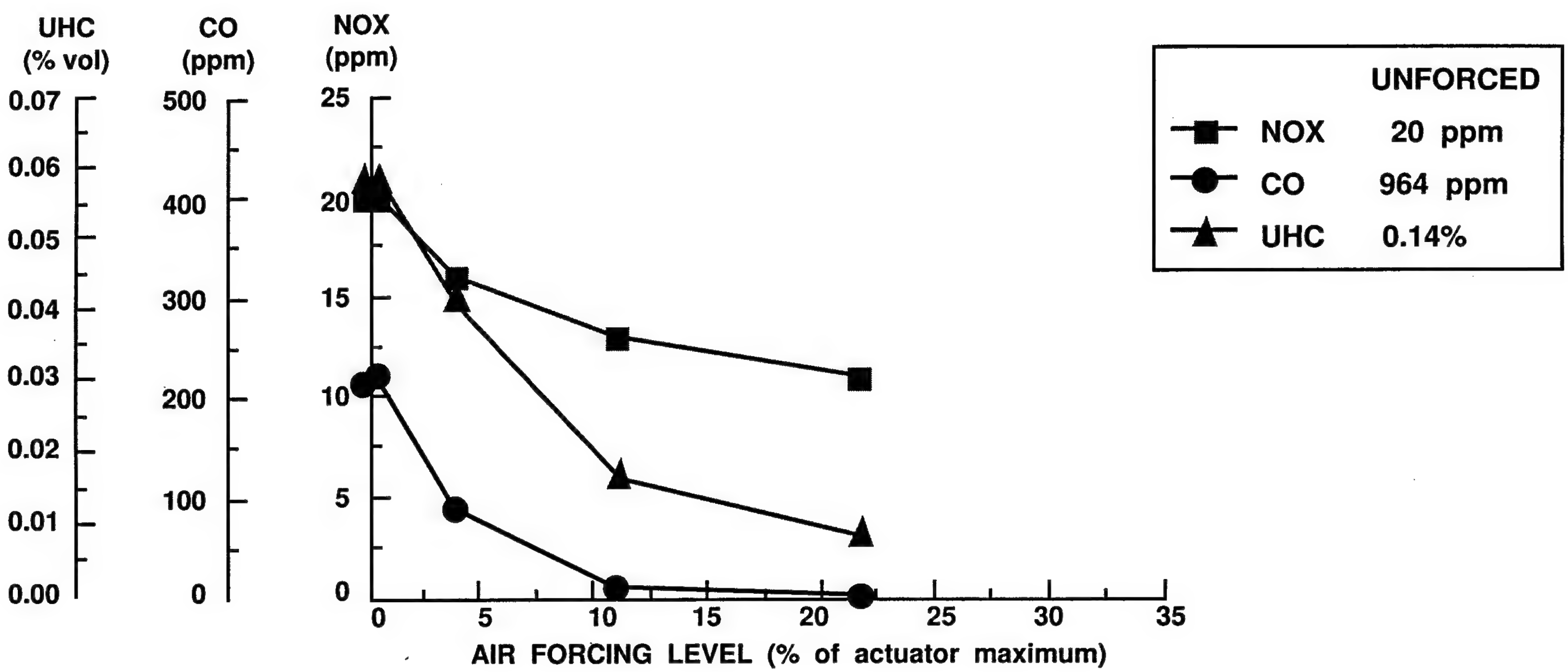
Effect of Vortex Strength on Combustion Efficiency



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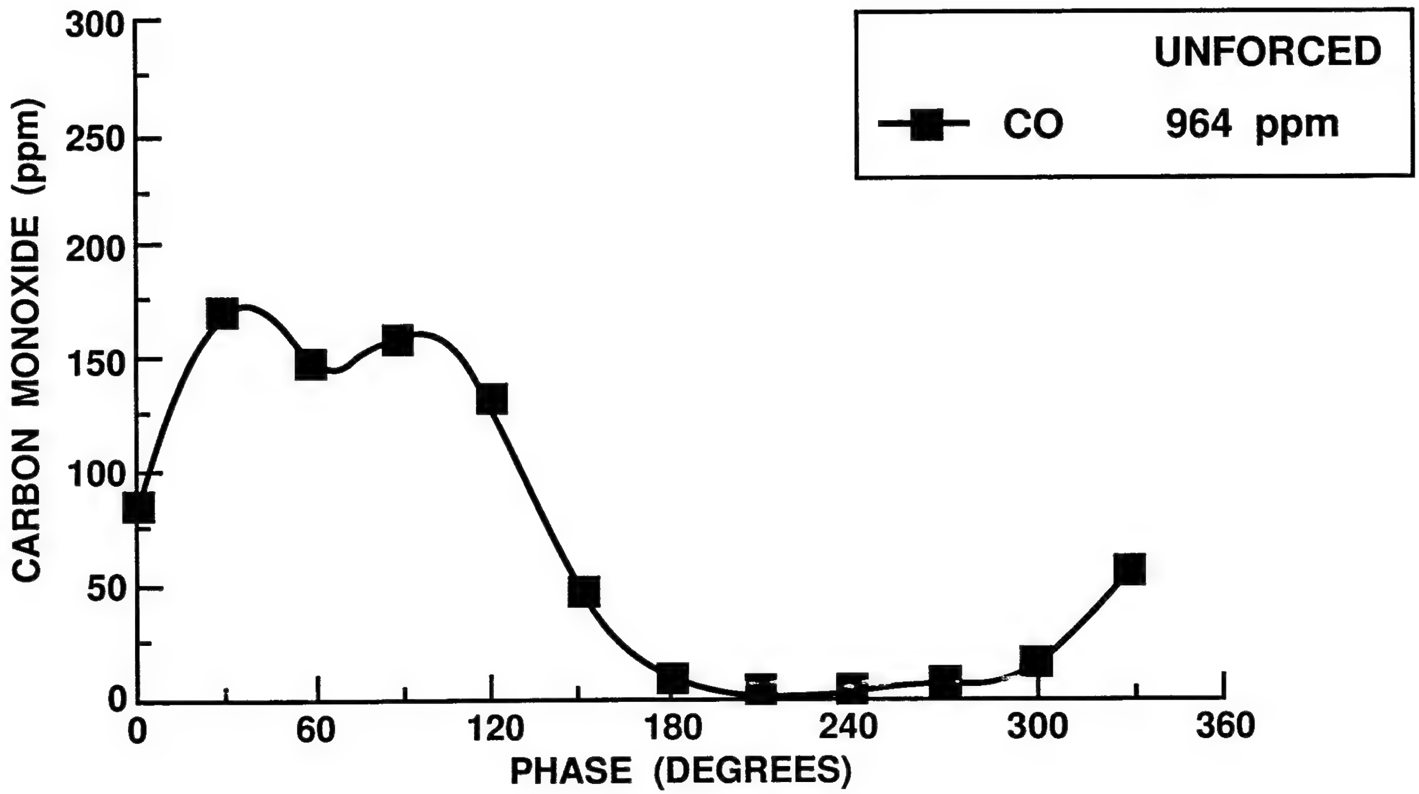
CO Reduction in Exhaust .vs. Relative Phase of Forcing



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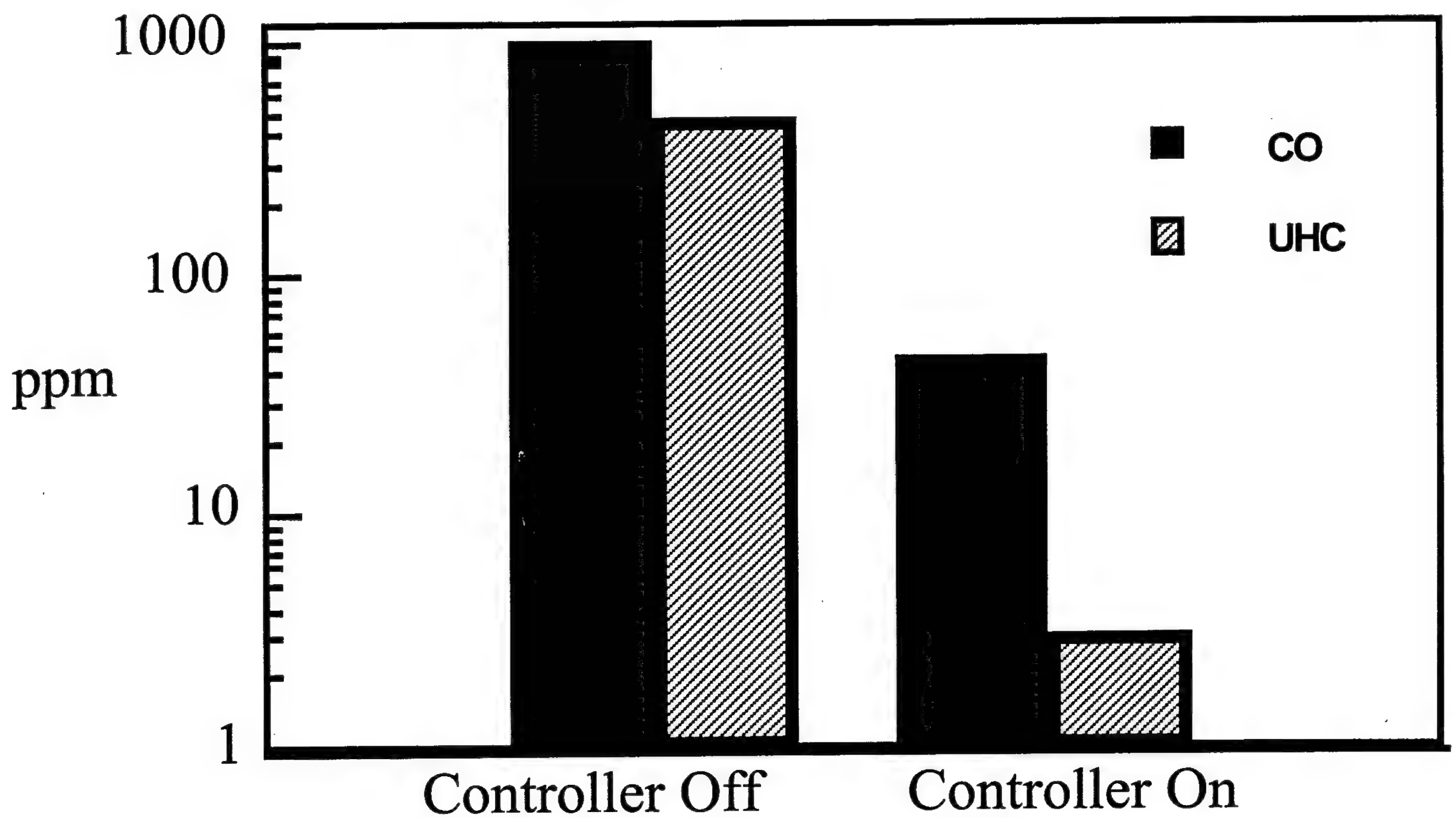
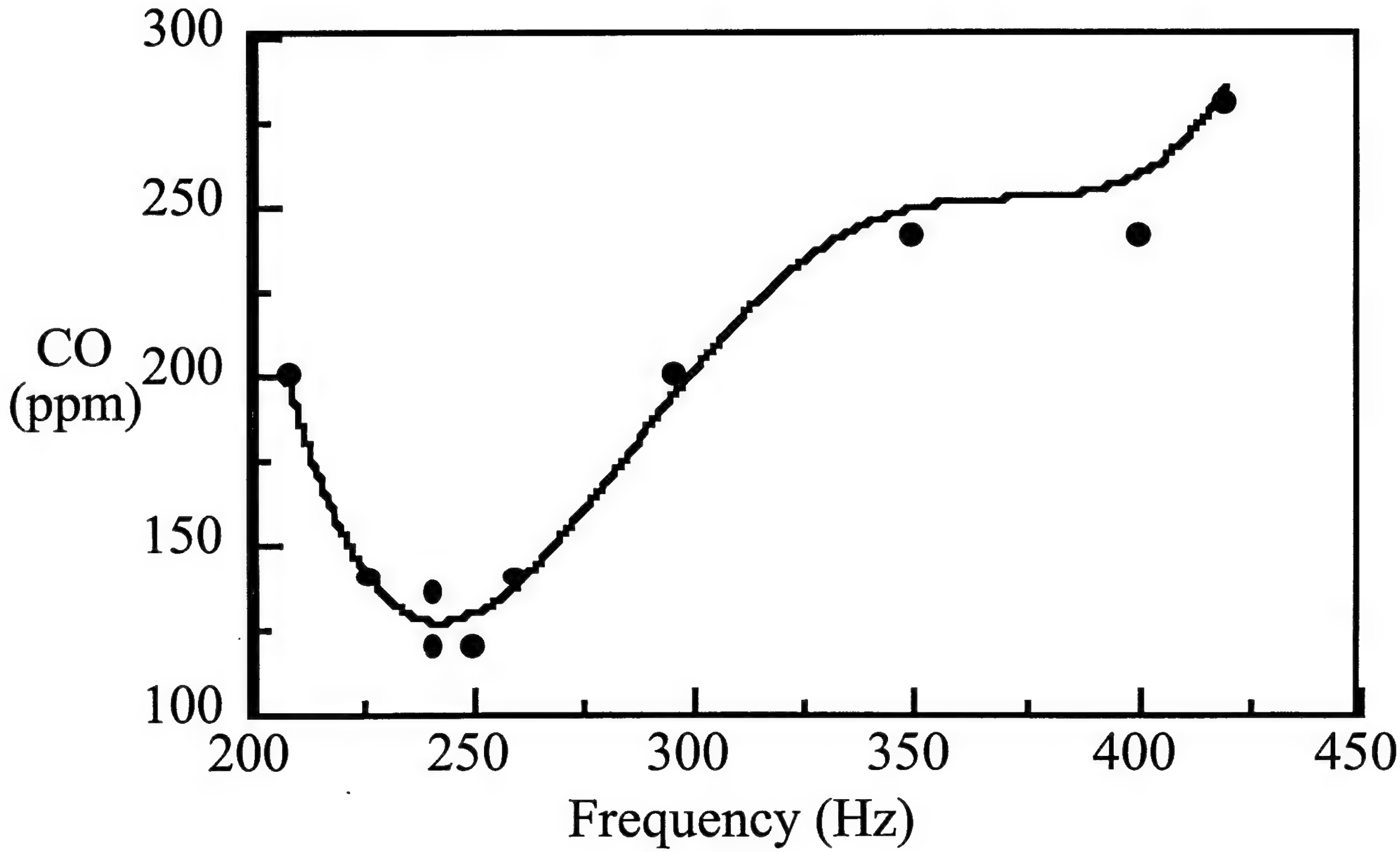
NAWC Weapons Division NAVAL AIR WARFARE CENTER

Effect of Active Control for a Scaled-Up Combustor (400 kW)

R&T Division Research Technology



Effect of Forcing Frequency (400 kW Combustor)



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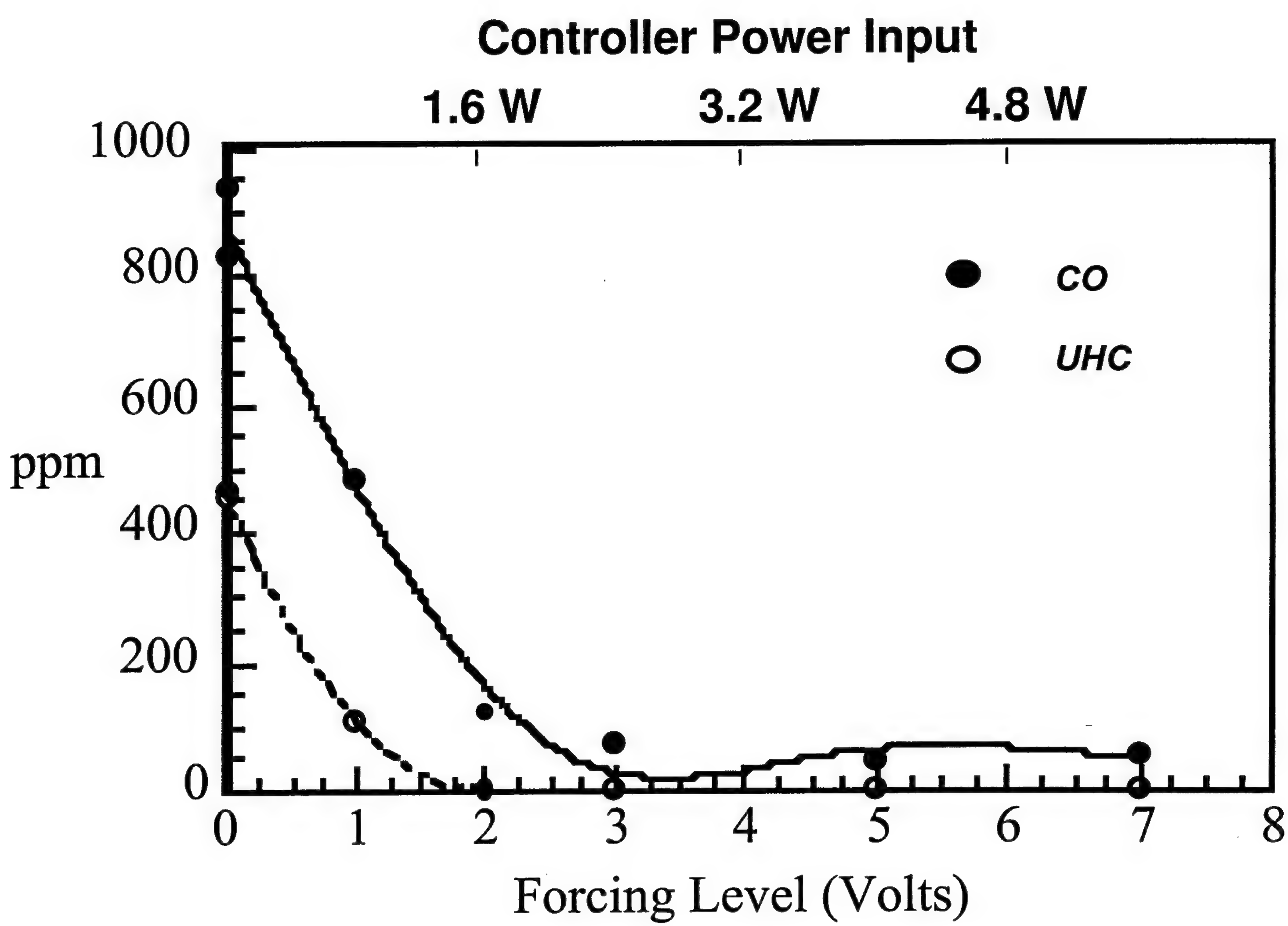
Effect of Forcing Amplitude (400 kW Combustor)



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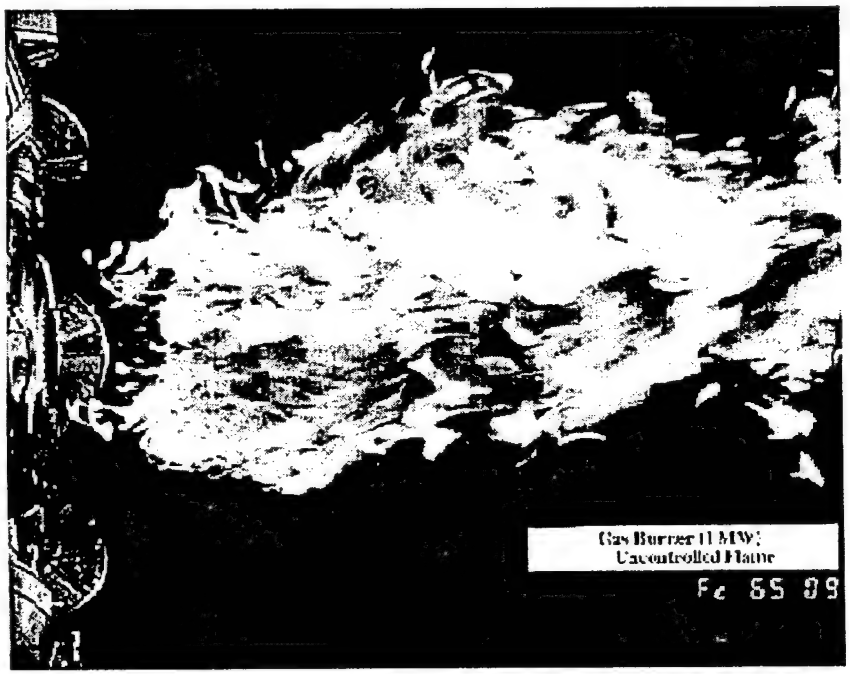
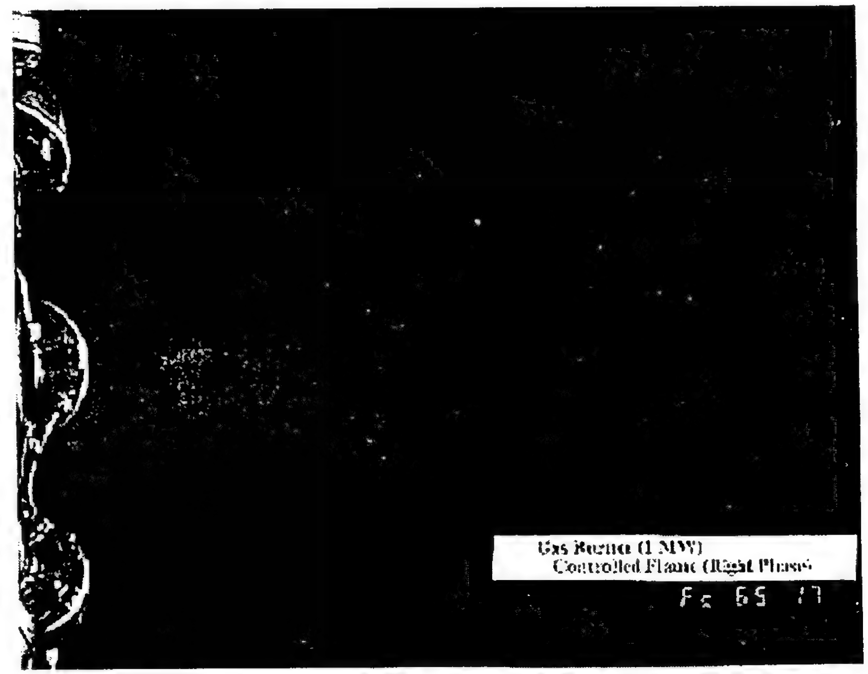
Weapons Division

UNCONTROLLED AND CONTROLLED 1 MW FLAME EXPERIMENTS

SERDP
Strategic Environmental Research and Development Program
A Partnership to Improve the Environment





NAWCWPNS

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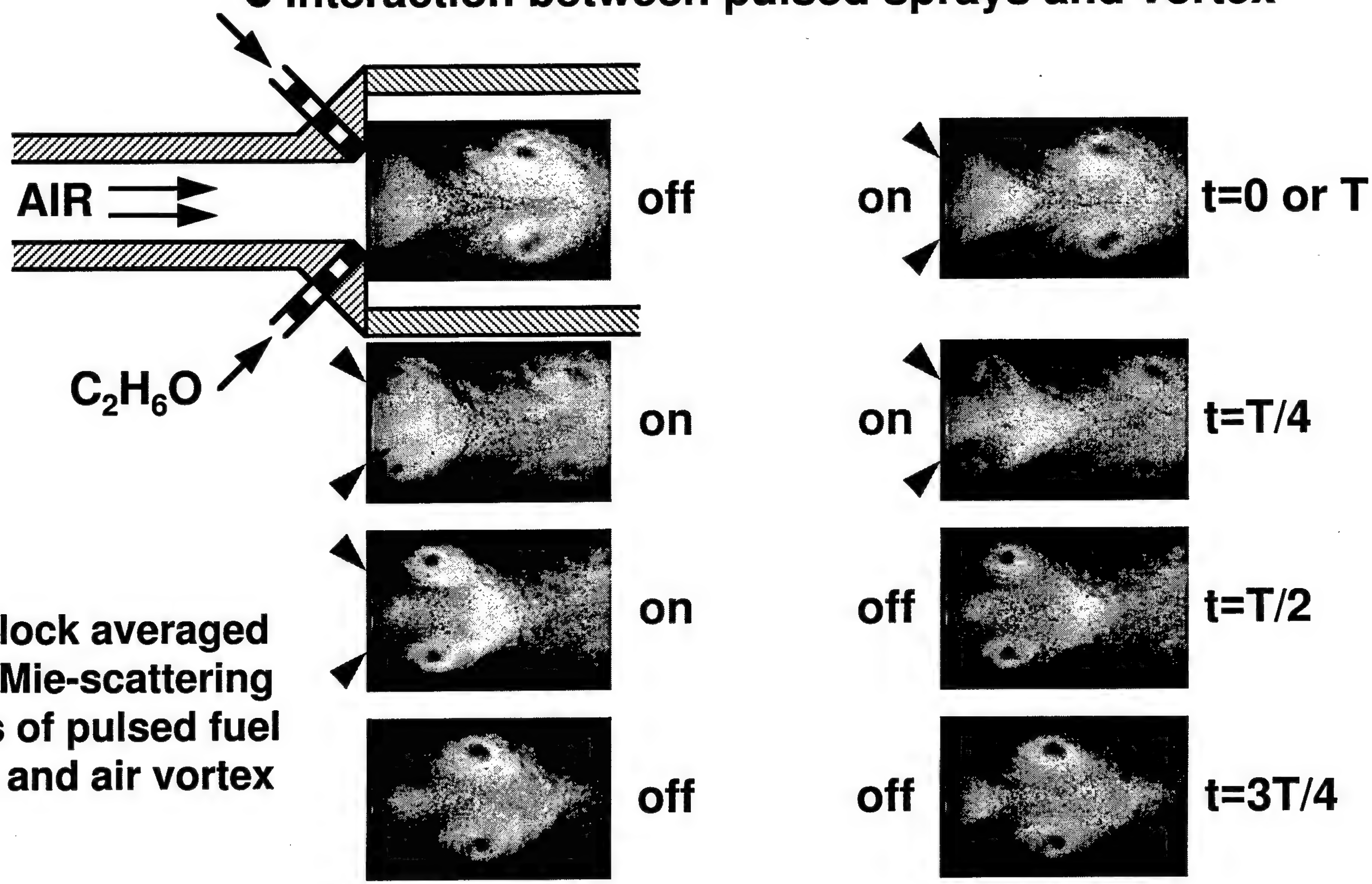
LIQUID-FUELED ACTIVE COMBUSTION CONTROL

- Interaction between pulsed sprays and vortex



- Phase-lock averaged planar Mie-scattering images of pulsed fuel sprays and air vortex

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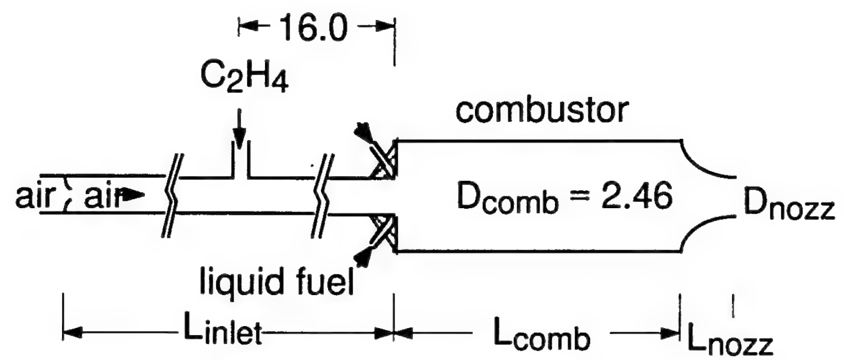
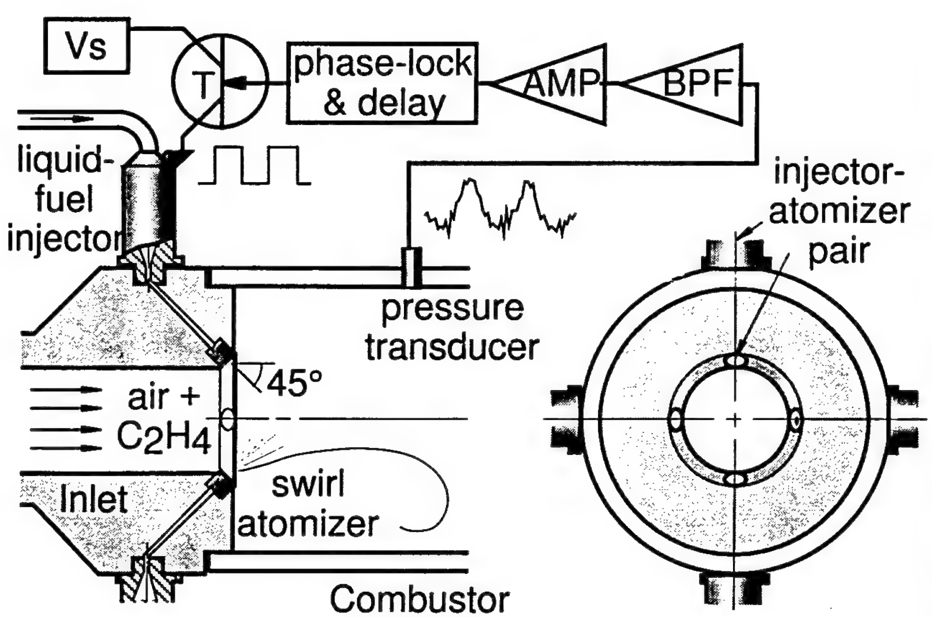
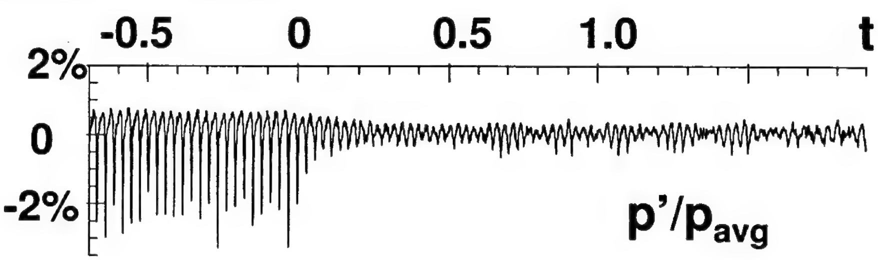
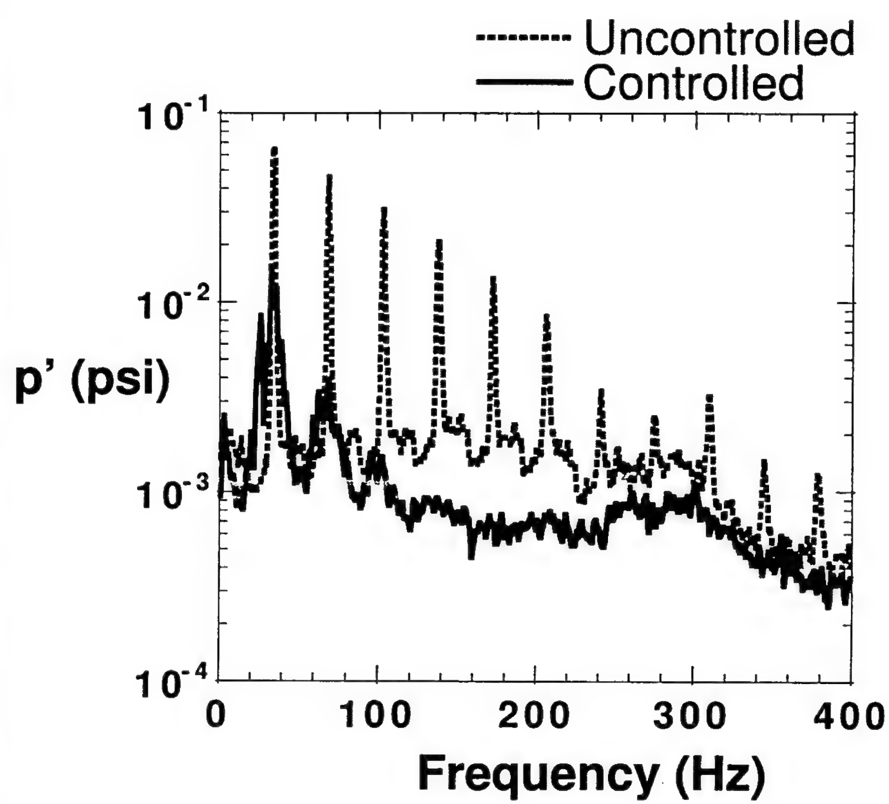
LIQUID-FUELED ACTIVE INSTABILITY SUPPRESSION









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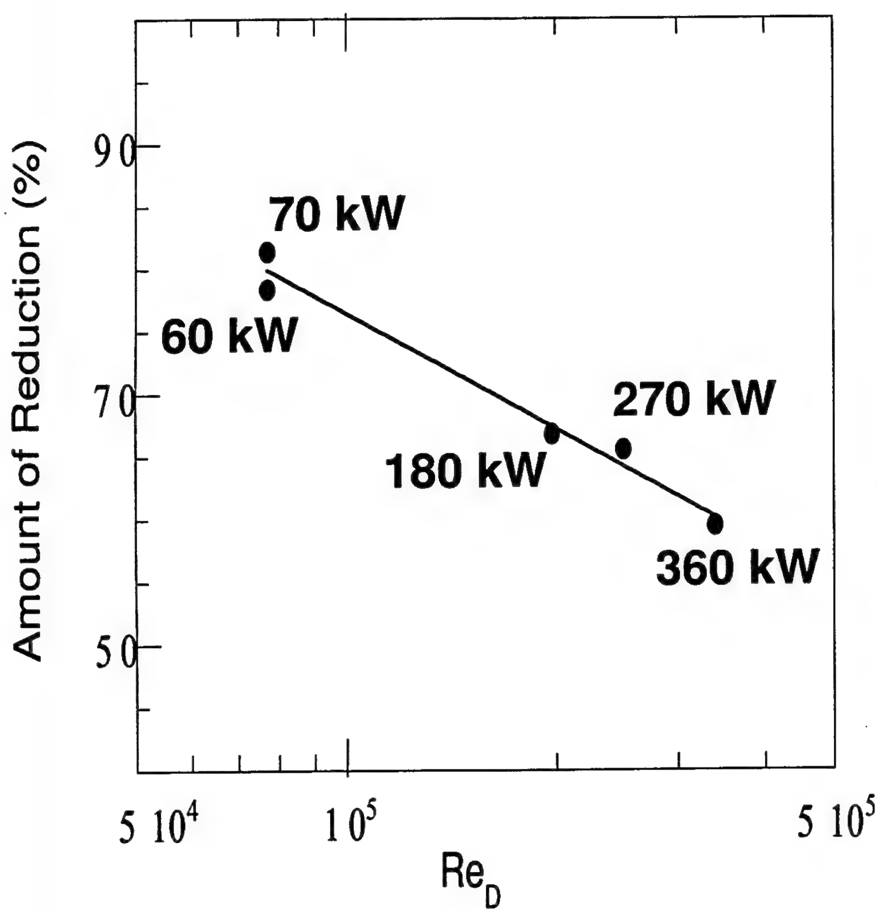
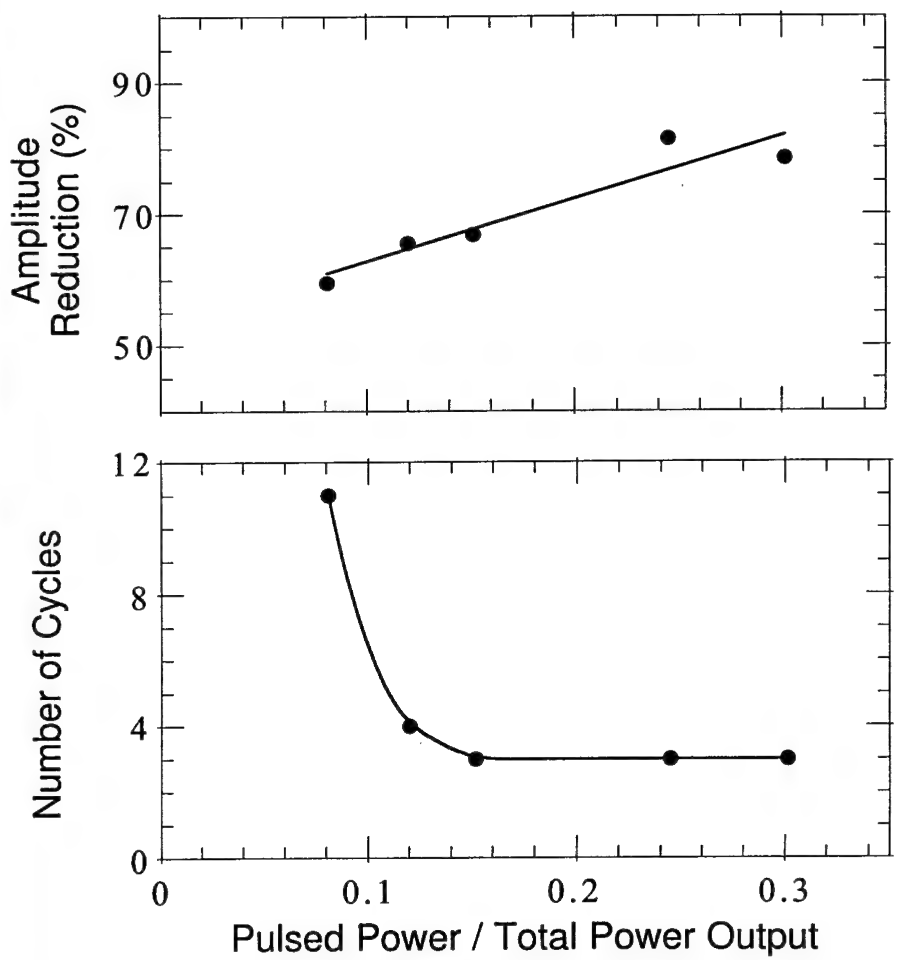
EFFECT OF SCALE-UP and Relative Amount of Pulsed Fuel





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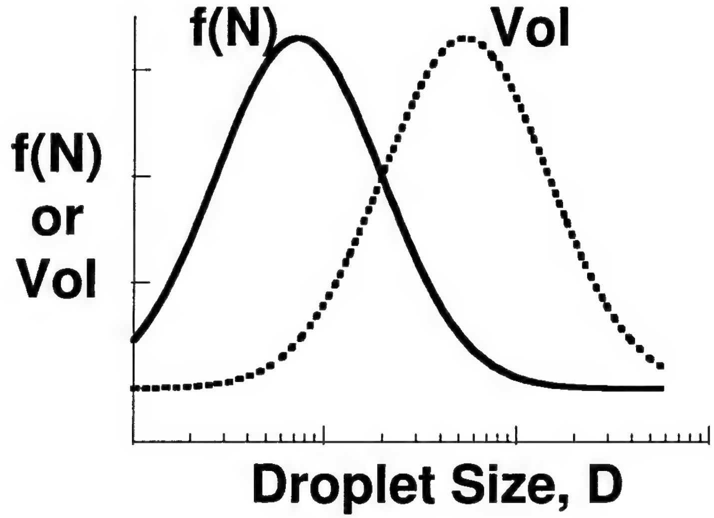
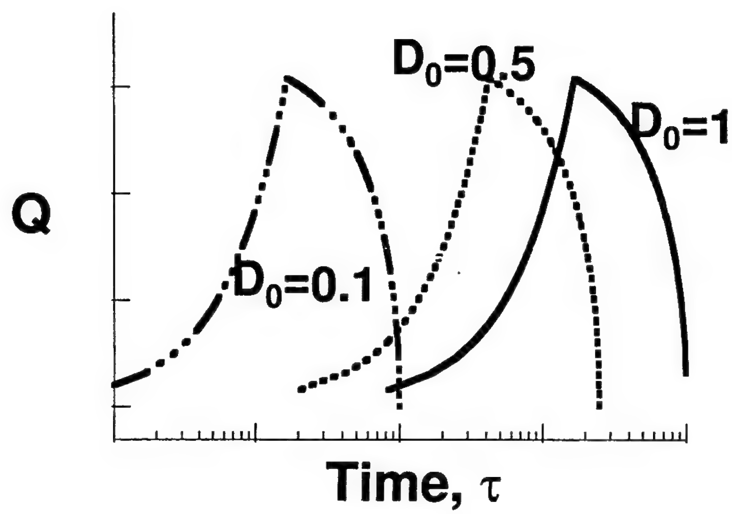
FUEL DROPLET SIZE





- Practical fuel injectors generate polydisperse sprays.
  - large number density of small droplets
  - big droplets with large mass fraction
- Droplet combustion behavior is determined by
  - ambient flow conditions
  - local equivalence ratio
  - presence of envelope flames
  - initial droplet size
- The time scales associated with heat release are effectively shortened by decreasing droplet size
  - $\tau_L \approx \tau_{Heating} + \tau_{Evapo} \propto D_0^2$

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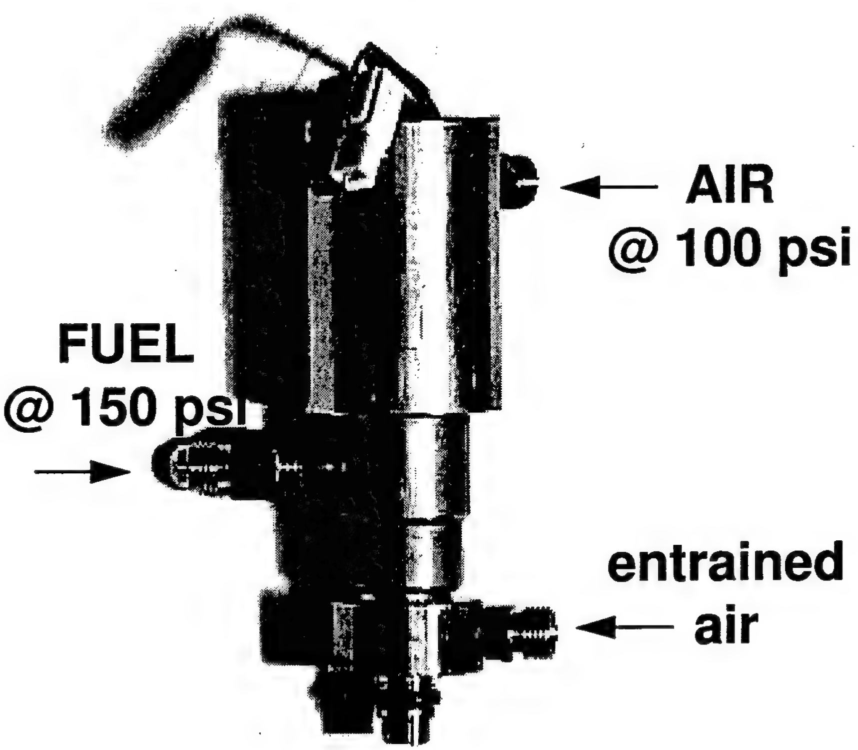
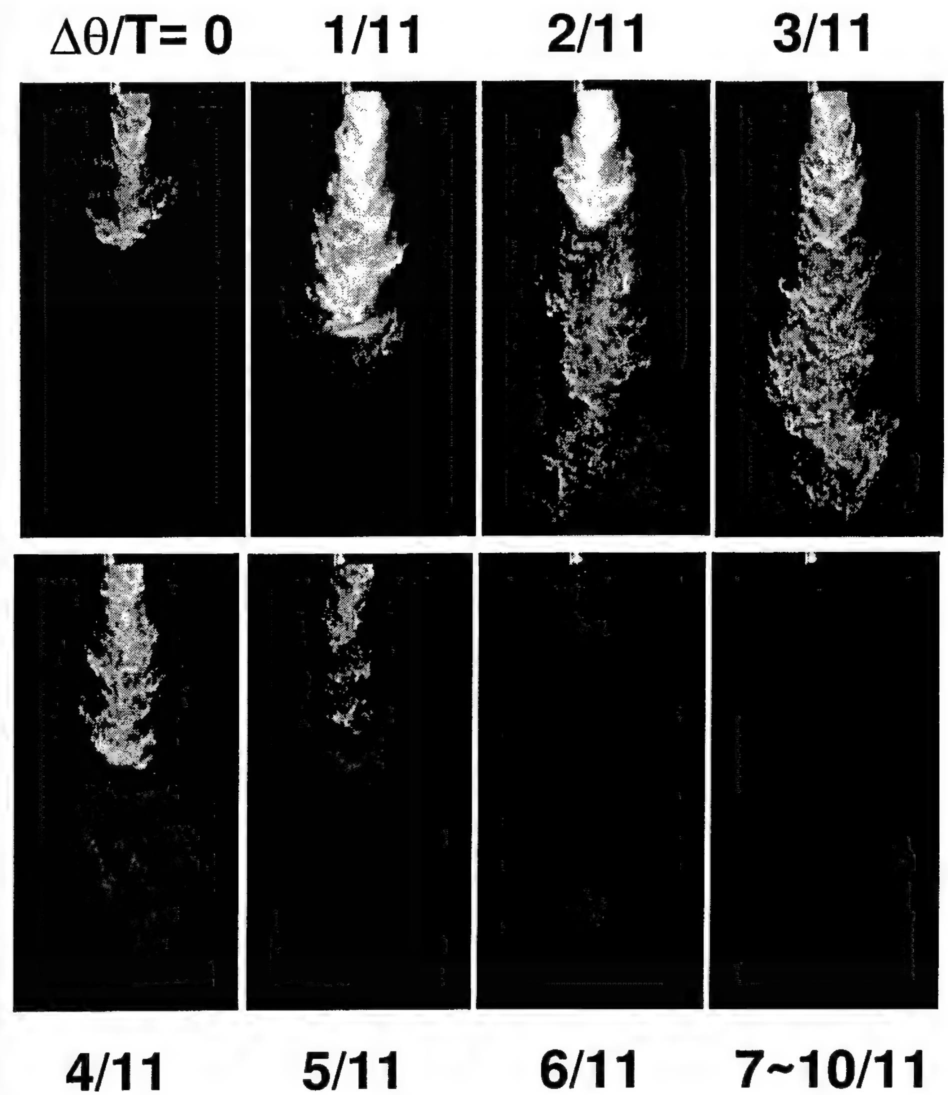
AIR-ASSISTED PULSED FUEL INJECTOR

- Pulses both air and fuel flow at frequencies of up to 150 Hz
- Flow Rate: ~ 3 gph @ 50% duty maximum range: 0.12 ~ 5.6 gph





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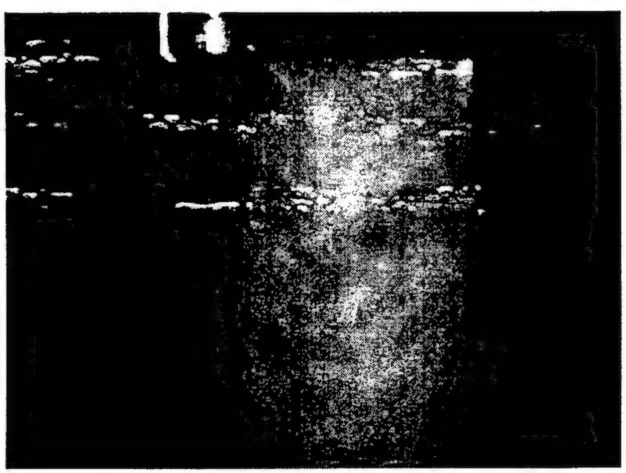
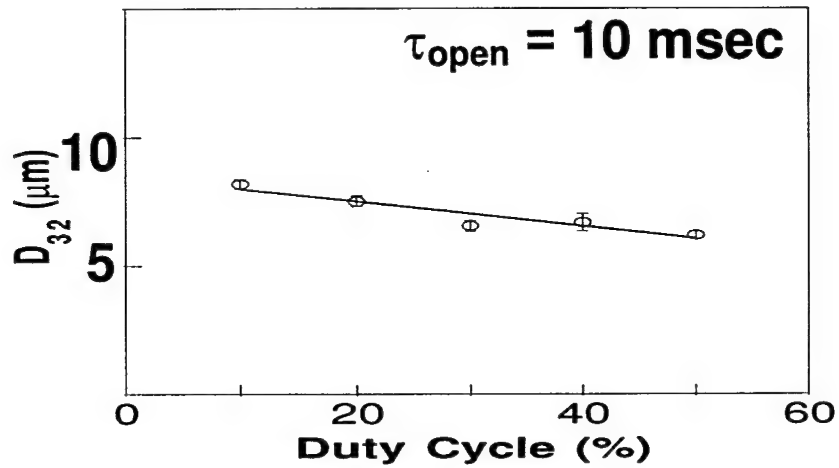
Dependence of Droplet Size on Duty Cycle and Frequency

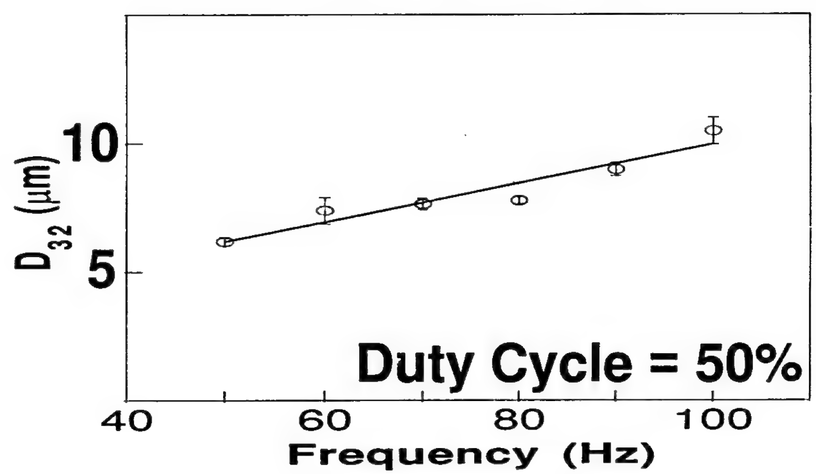
Instantaneous $(\Delta\theta / T = 0.4)$

Phase-Averaged



- JP-10 @150 psi and air @100 psi (Malvern Measurement at x=2")





NAWC Weapons Division NAVAL AIR WARFARE CENTER

PULSED FUEL INJECTION

R&TD DIVISION TECHNOLOGY RESEARCH

- EFFECTIVE MEANS TO APPLY ACTIVE COMBUSTION CONTROL
  - SIGNIFICANTLY REDUCED CONCENTRATIONS OF UHC, CO, AND NOx (GASEOUS FUELS)
  - SUPPRESSED COMBUSTION INSTABILITIES BY 15 dB (LIQUID FUELS)
- UNDERSTANDING OF PHYSICAL MECHANISMS CRITICAL FOR PROPER APPLICATION
  - PULSED GASEOUS FUEL INJECTION MODIFIES TURBULENT MIXING BETWEEN FUEL AND AIR
  - PULSED LIQUID FUEL INJECTION AFFECTS FUEL DROPLET DISPERSION CHARACTERISTICS
- SCALE-UP AND OPTIMIZATION STUDIES IN PROGRESS
  - GASEOUS FUEL COMBUSTOR SUCCESSFULLY SCALED UP BY A FACTOR OF 200
  - CRITICAL ROLE OF PULSED FUEL FLUX AND DROPLET SIZE IDENTIFIED FOR LIQUID FUEL COMBUSTOR

Air Force
Research Laboratory | AFRL
Science and Technology for Tomorrow's Air and Space Force

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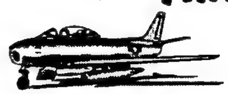
ACTIVE CONTROL TECHNOLOGIES FOR AIRCRAFT ENGINES

"If this is to be a revolution, then let's make the most of it!"

. . . . Someone Famous

Stephen J. Przybylko **Turbine Engine Division**

Introduction

- **Ancient History:** Vacuum-tube electronics introduced

  on B-52's & F-86's ca. 1950's.
- Poor performance results in hydromechanical domination for two decades.
- Semiconductor-based electronics creep back on-board.
- Today, microprocessor-based FADECs dominate.
- Greatly increased power enables host of new control schemes, including Active Controls.
- **Payoff:** Better system performance thru improved component performance.
- **Challenges:** Implementation technologies (sensors/actuators).

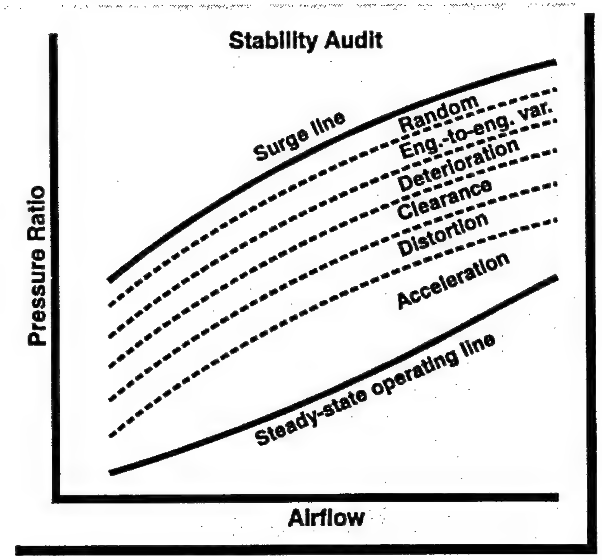
What does **Active Control** mean anyway?!

- **Stabilizes an unstable system.**
- **Higher bandwidth than previous controls.**
- **Closed-loop control of previously open-loop control.**
- **Controls something that has not been controlled before.**
- **Just another buzzword ($$$, grants, papers, etc.)!**

. . . . so why not ***Extreme*** CONTROLS?!

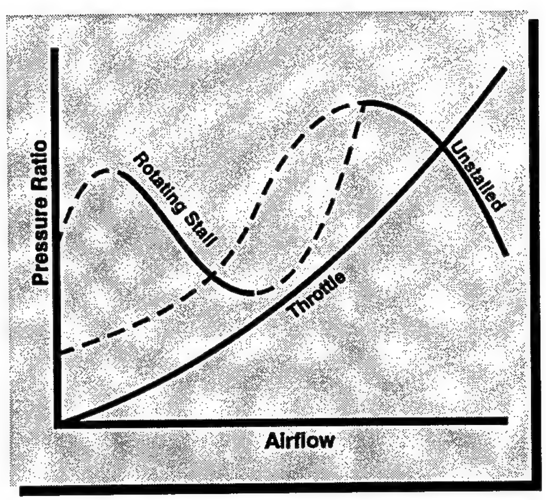
Active Control of Compression Systems

- **Addresses decades-old problem (Surge detection/elimination).**
- **Microcosm of all that is good & difficult regarding active controls.**
- **Significant payoffs thru reduction of surge margin.**
- **Retrofittable to existing engines:**
    - Fix in-service problems
    - Margin reduction via trim or algorithm redesign.
- **Greatest payoff is for new centerline engine:**
    - Smaller compressor
    - Elimination of stage(s).
- **Possible diagnostic aid.**



Moore-Greitzer Model

- Accounts for dynamic interaction of pressure-rise vs. airflow characteristics with the 2-D flow field.
- Widely used by academia and 6.1 researchers.
- Displays hung stall, limit cycle, and hysteresis exhibited by surge.



- Actuator Disc/Lumped Volume
- 3-State Variables
- Ordinary Differential Equations
- Nonlinear
- 2-D Flow
- Cubic Flow Characteristics
- 2nd-Order Throttle
- Exhibits Bifurcation

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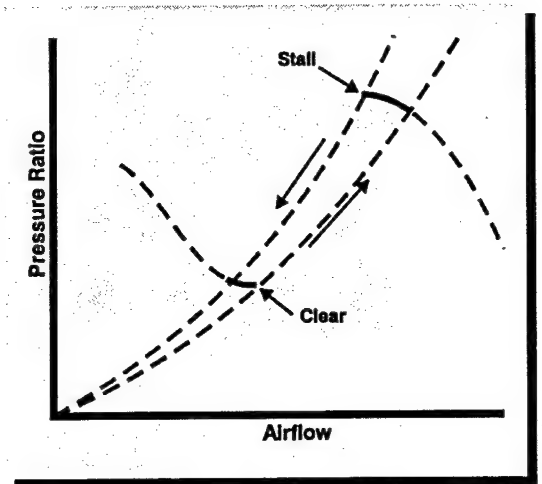
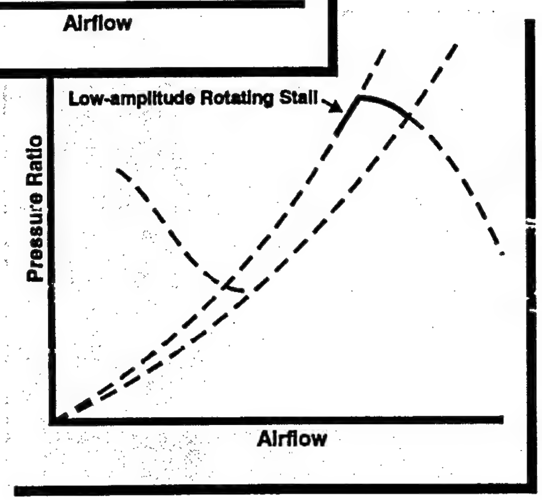
Demonstration





- Demonstrated on low-speed rig at UTRC.
- Moore-Greitzer based.
- Employed bleed valves.
- Eliminated surge hysteresis.

Suggested need for high-response bleed valves for a real system!

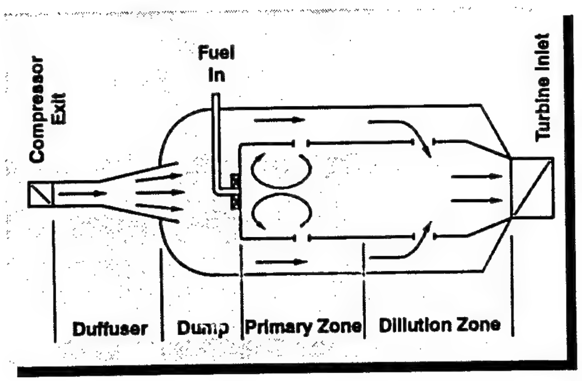
Engine-level Benefits

If Active Stability Control, along with other surge-margin-reducing technologies, can eliminate one stage of compressor in a new engine design, then the following benefits can be realized:

- ❑ +5% Fn/Wt
- ❑ -1.5% SFC
- ❑ -3.2% Acquisition $
- ❑ -1% Operating $
- ❑ Stall-free operation
- ❑ Extension of maintenance intervals
- ❑ Allow increased inlet distortion

Active Combustor Control

- Challenging environment.
- Highly complex aerothermal-chemical processes.
- Very much an Art!
- Quintessence of passive control.

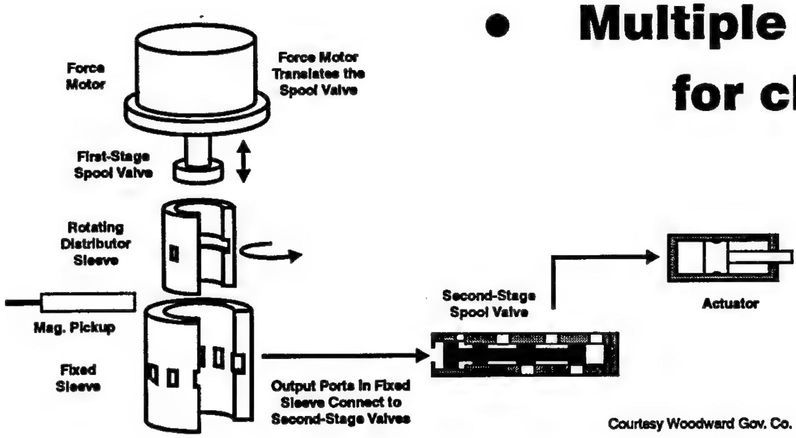


Possibilities:

- Pattern-Factor Control
- Reduction of Emissions
- High-Cycle Fatigue

Pattern-Factor Control

- Ideal combustor exit profile: Absolutely smooth circumferentially, slight radial profile (cooler at blade roots).
  - Hot spots shorten turbine life.
    - Improving profile allows higher average turbine-inlet temperature with minimum affect on life.
      - Individual control of fuel injectors required.
        - Multiple temperature sensors required for closed-loop control.



Courtesy Woodward Gov. Co.

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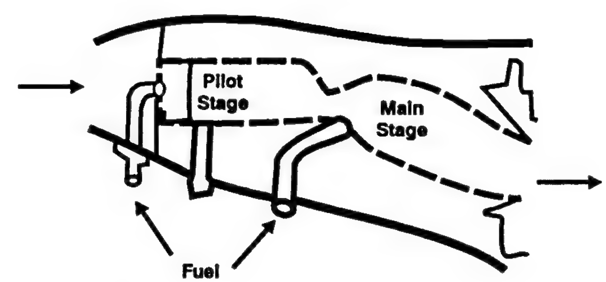
Control of Emissions

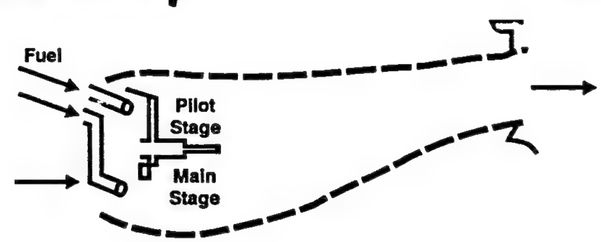
- **Contemporary issue is NO_x.**
- **Control of local fuel/air ratio is critical.**
- **NO_x is a function of temperature and time at temperature.**
- **Two approaches:**

  Quick quench - Locally rich for stability, lean for low NO_x, mix quickly.

  Lean burn - Uniform burning throughout.

- **Complication: Combustion instability!**





High-Cycle Fatigue

- **Combustion instabilities can be damaging to structure.**
- **Tend to occur under lean-burning conditions.**
- **Two approaches to control:**

  Low-bandwidth mode -

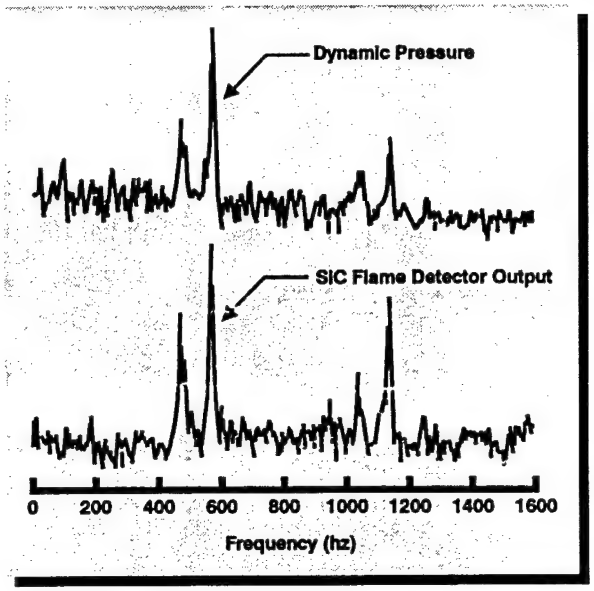
  - Closed-loop control to not exceed lean-burn limit.
  - Requires appropriate sensors.
  - One dimensional or individual injectors.

  High-bandwidth mode -

  - Borrow from active noise control.
  - Sensors and actuators (injectors) must be high response.

Combustor Challenges

- Extremely high temperature environment.
- Variable geometry would be useful--but what can survive?
- High-temp./high-response sensors and flow-control devices needed.
- Multiplicity of sensors and control valves.



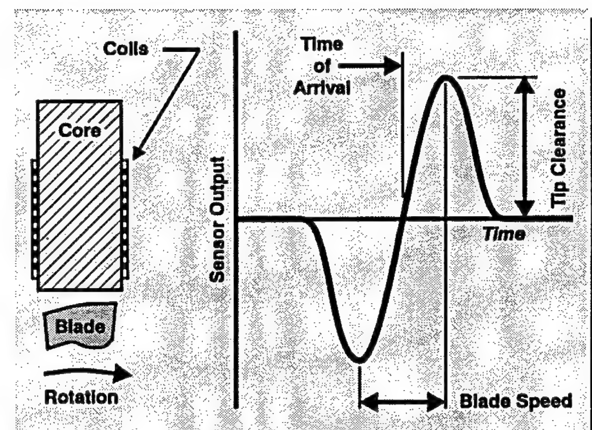
Is there hope?

- Fluidics.
- Silicon carbide sensors/electronics.
  - UV detector for HCF and NO_x control.
- MEMS/Mesoscopic machines.

More realistic to first apply active control to nonaeroderivative industrial turbine engines.

Active Structural Control

- **Reduce, eliminate, protect against vibration.**
- **Unconventional geometry control:**
  - Flow-path area/vanes.
  - Clearances.
- **Vibration is costly maintainance issue.**
- **Forcing functions:**
  - Shaft dynamics.
  - Blade passage.
  - Flame instabilities.
  - Acoustic resonances.



Courtesy Lucent Technologies

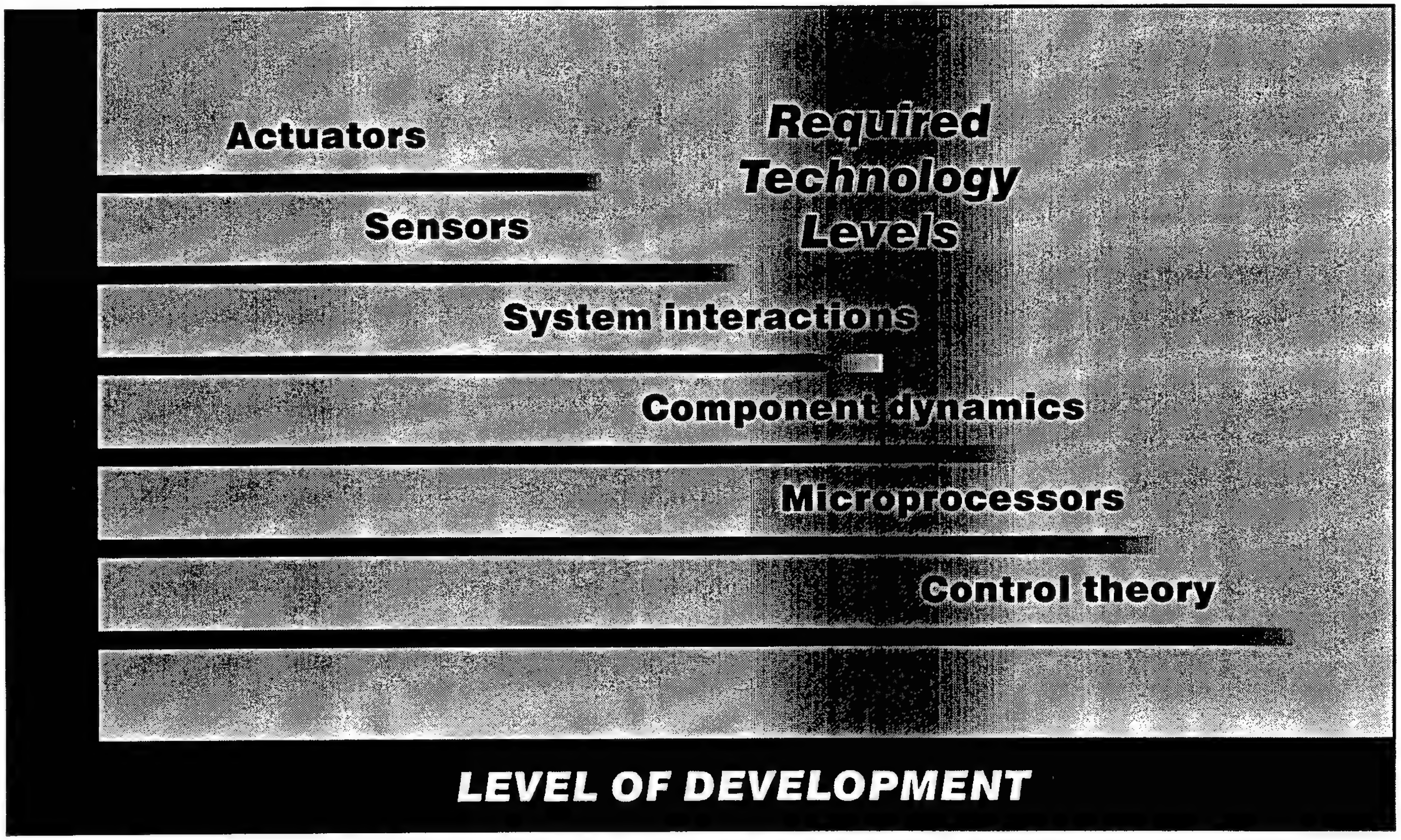
Dealing with vibration:

- Eliminate the source.
- Active damping
- Avoidance

General Observations

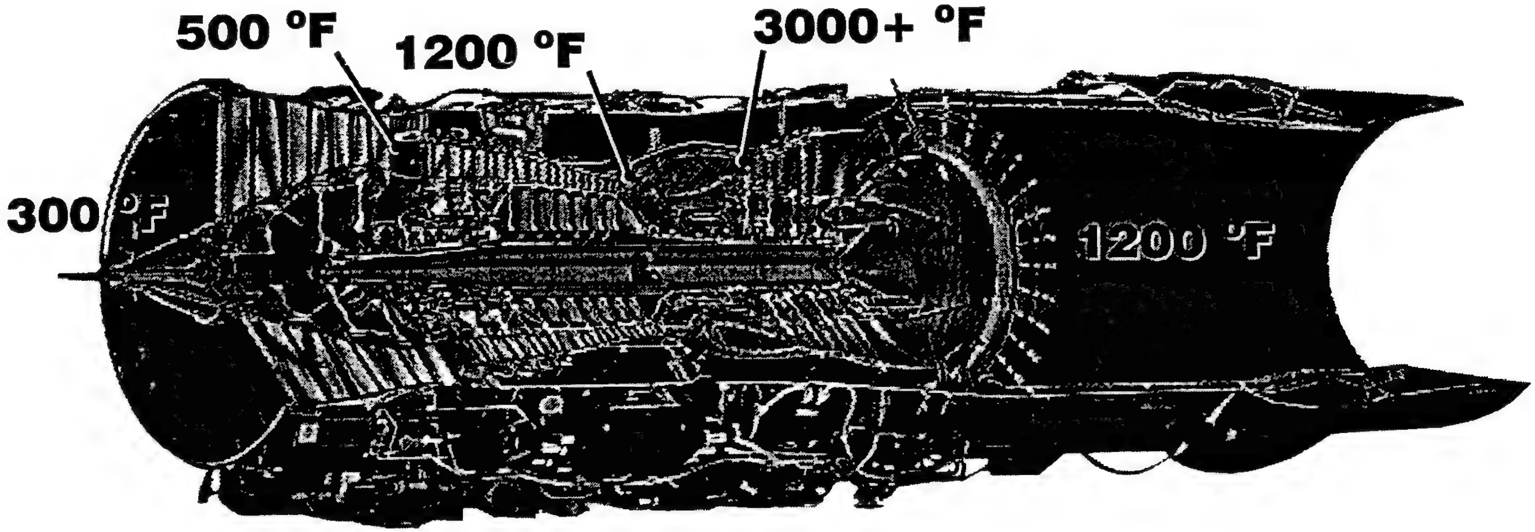
- Active controls tend to focus on individual components, though system benefits are usually realized.
- Benefits are usually due to reductions in margins.
- Benefits can be achieved thru retrofit.
- Largest benefits are realized when active controls are designed into new-centerline engines.
- A multitude of sensors and actuators is often required.
- Sensors must survive in high-temperature environments.
- Actuators must be high response.
- Active controls can compensate for errors or omissions in the design of the engine.
- They can compensate for problems resulting from in-service degradation.
- They often deal with parameters which are of diagnostic interest.

State-of-the-Art Requirements



Engine Environment

Typical operating temperatures

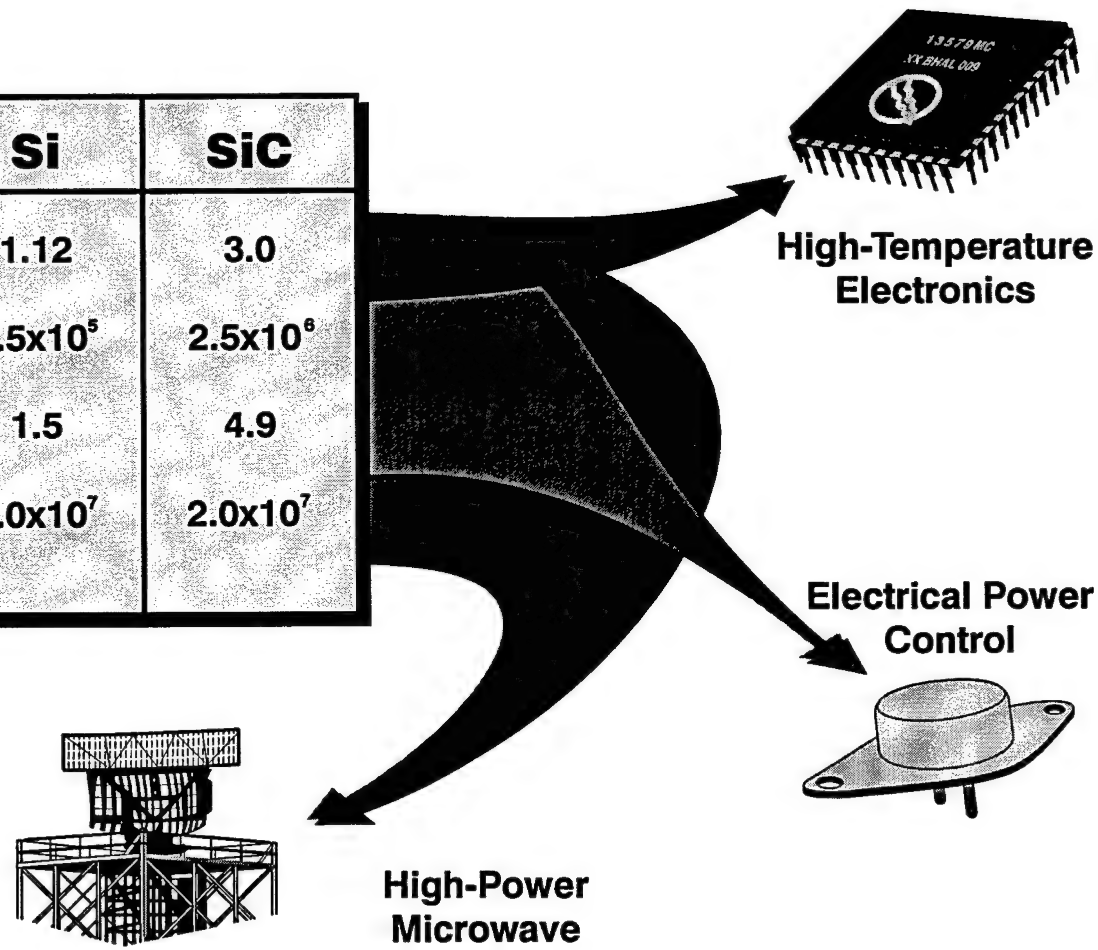


Case vibrations: 100 g's out to 20 khz

Acoustic sound levels: 120 db/hz out to 10 khz

Semiconductor Properties vs Applications

	Si	SiC
Band-gap Energy (eV)	1.12	3.0
Breakdown Electric Field (V/cm)	2.5×10^5	2.5×10^6
Thermal Conductivity (W/cm°K)	1.5	4.9
Saturated Electron Drift Velocity (cm/sec)	1.0×10^7	2.0×10^7



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SiC for Active Control

Pressure sensor -

Op. amp. (GE CR&D) combined with SiC pressure sensor (Kulite) will result in an integrated pressure sensor with high-temperature capability for active stability control and distributed control. May lead to the development of accelerometers for HCF control.

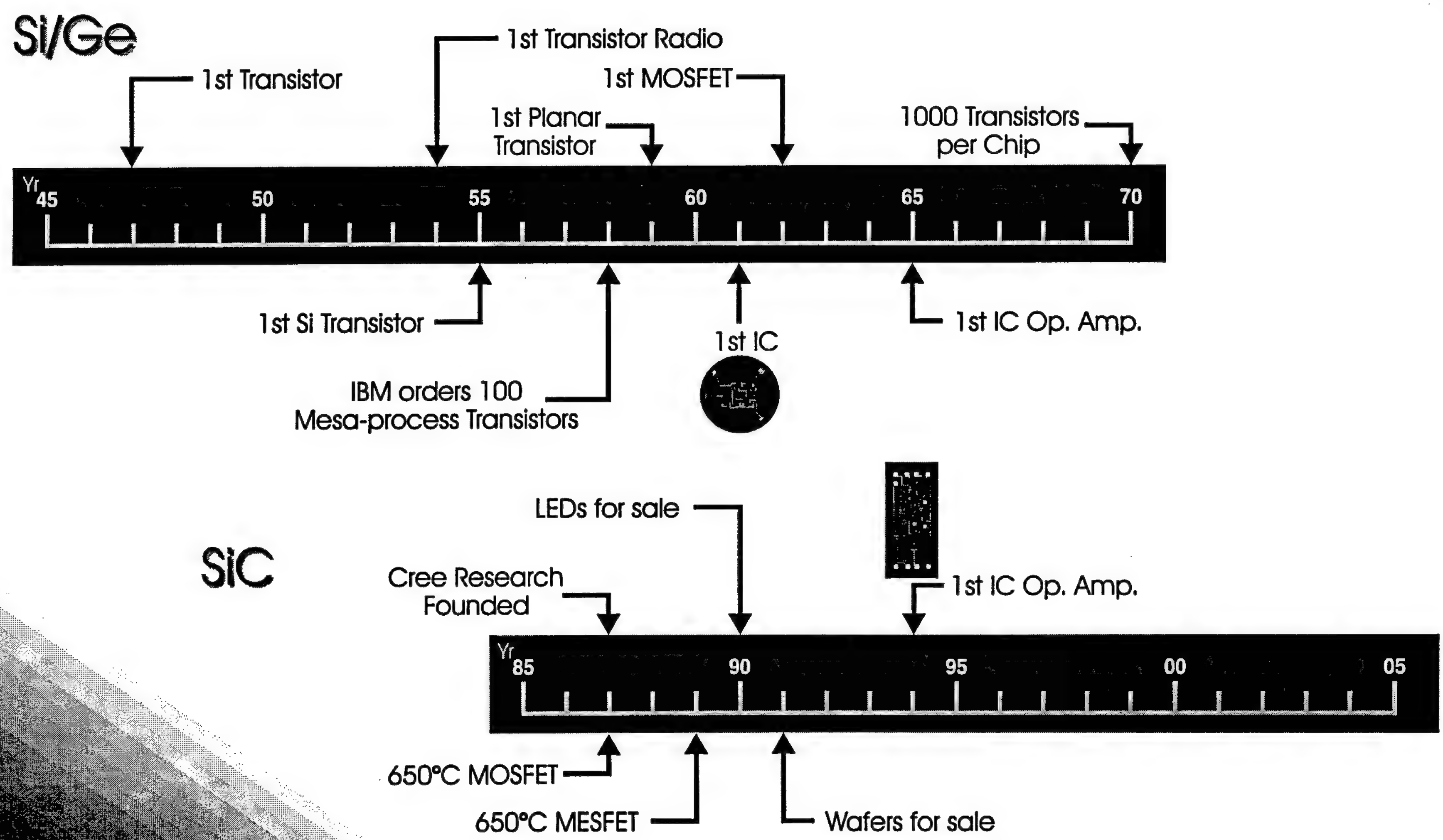
UV detector -

Ability to sense flame presence, flicker, and temperature provides great potential for use in active combustor control concepts and possibly HCF.

Power electronics -

Unidentified potential to control electrical power for actuators.

SOLID-STATE HISTORY



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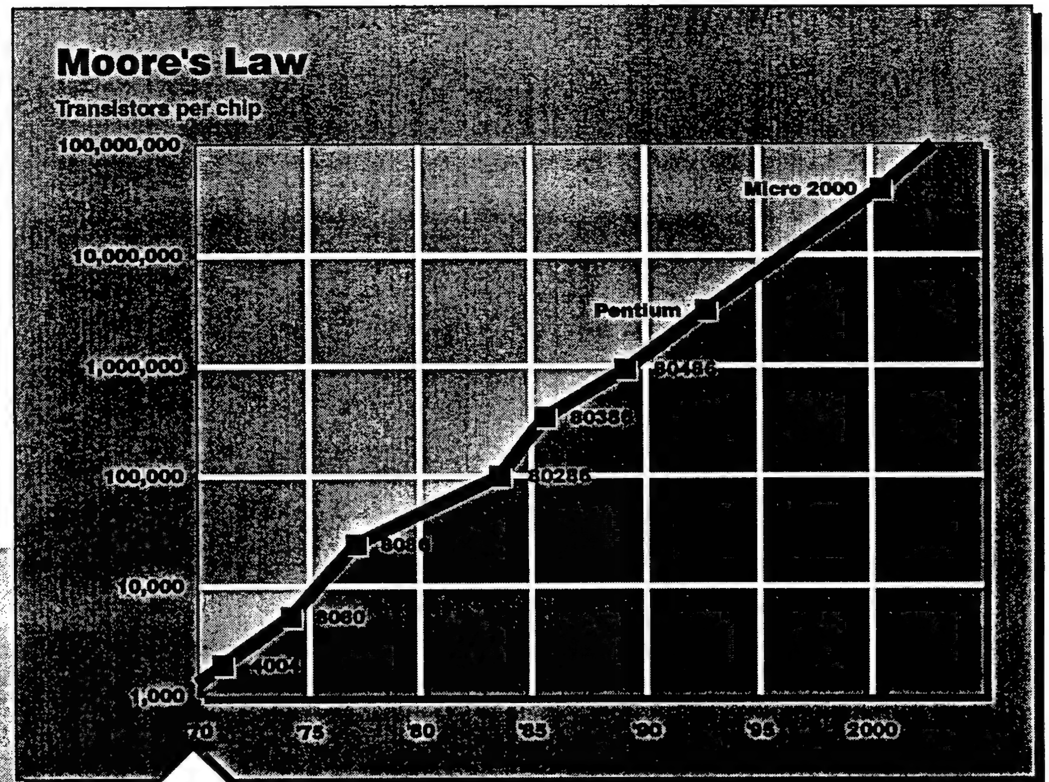
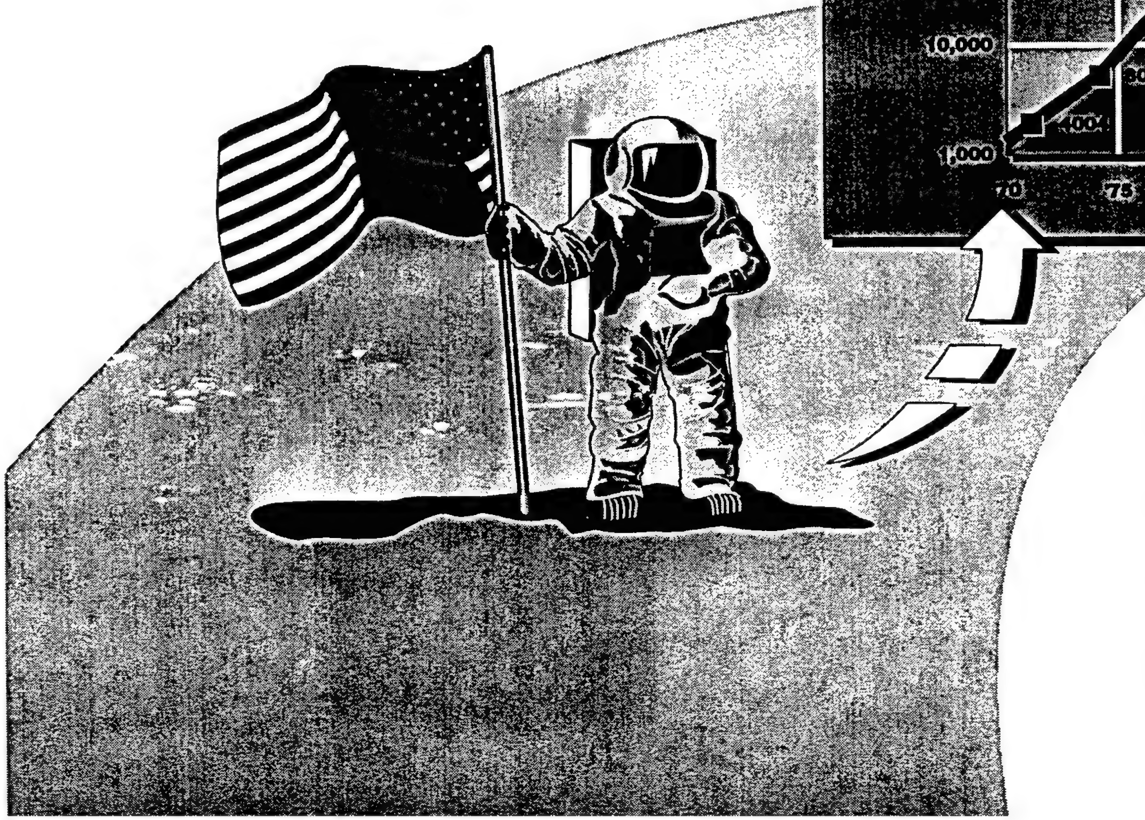
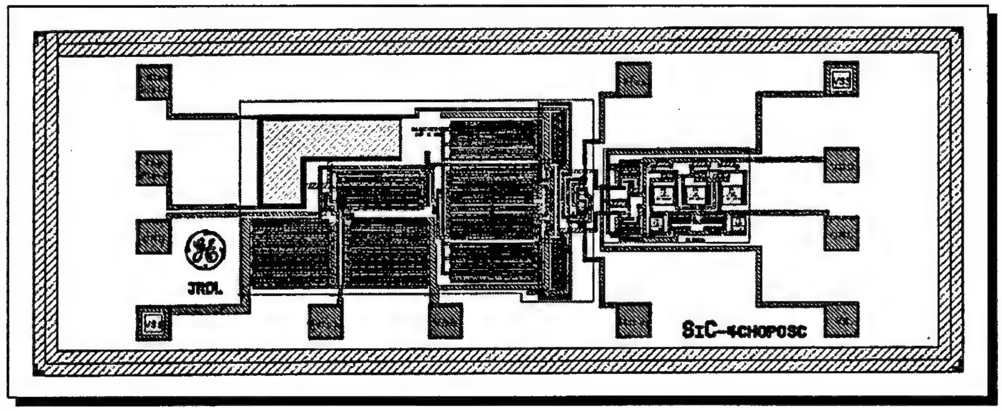
Useful solid-state electronic systems are doable with a low level of circuit integration.





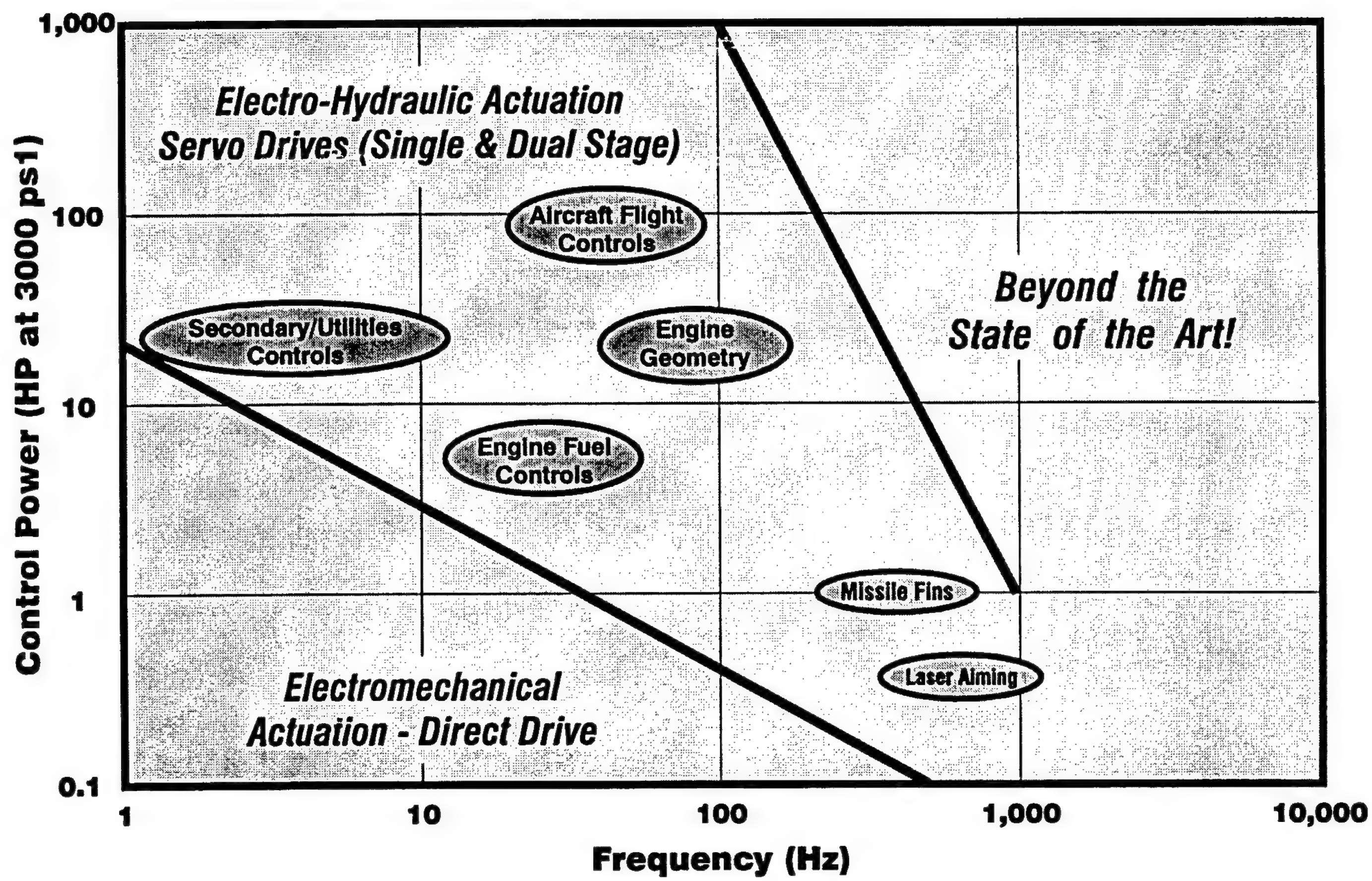
When men walked on the moon, the level of integration was about one thousand transistors per chip!

Silicon Carbide Op-Amp

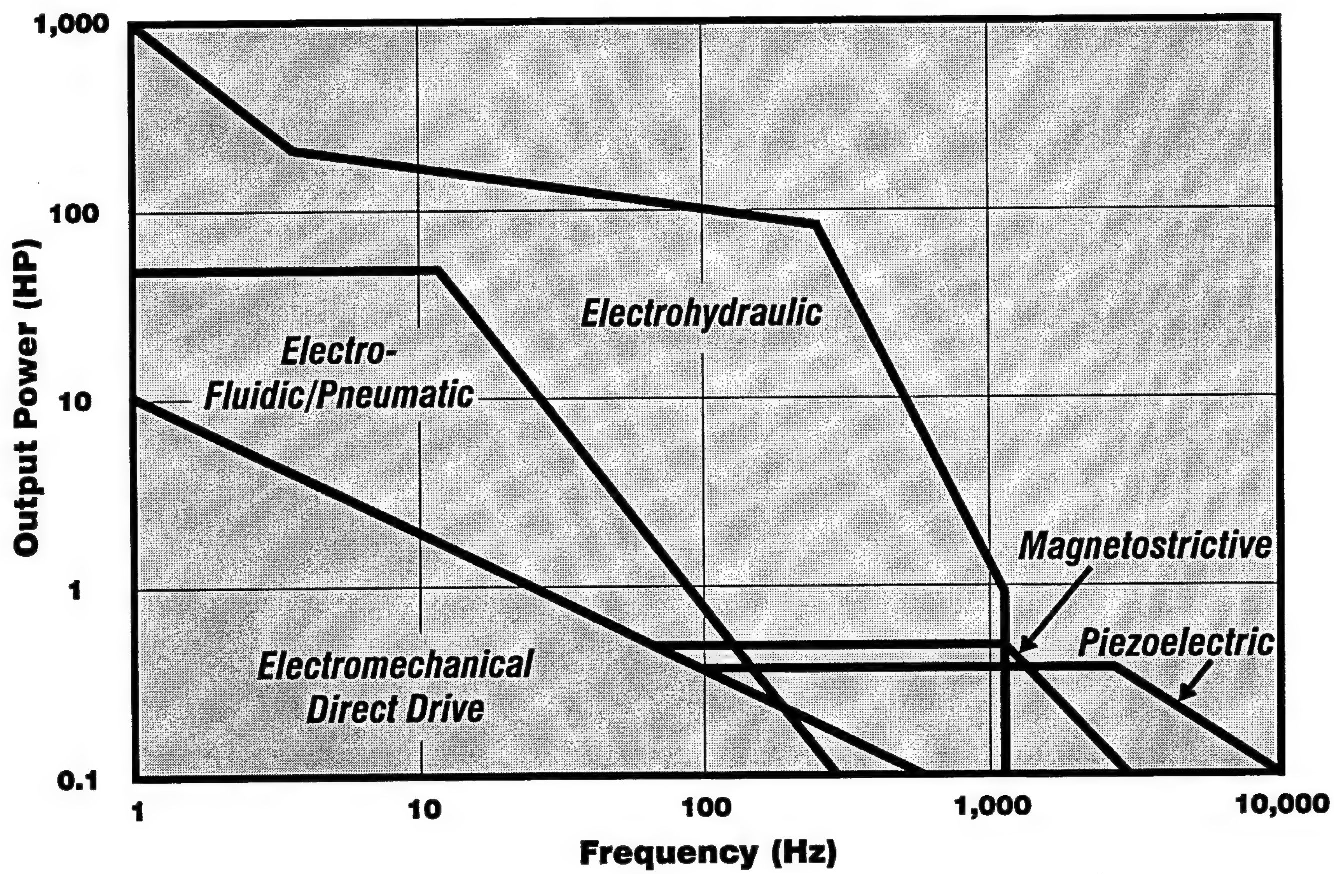


- Chopper stabilized
- Includes offset-cancellation circuit
- Includes chopper oscillator
- Includes compensation capacitor
- 2 micron design rules
- Die size: 2700 by 1000 microns

Servo System Bandwidth vs. Power



Technology Bandpass vs. Power



Mixing Control using Synthetic Jets

Staci Edlund[1], Brian Ritchie[2], Jerry Seitzman[2], and Ari Glezer[1]

[1]Woodruff School of Mechanical Engineering
[2]School of Aerospace Engineering
Georgia Tech

Supported by ARO-MURI DAAH04-96-1-0008

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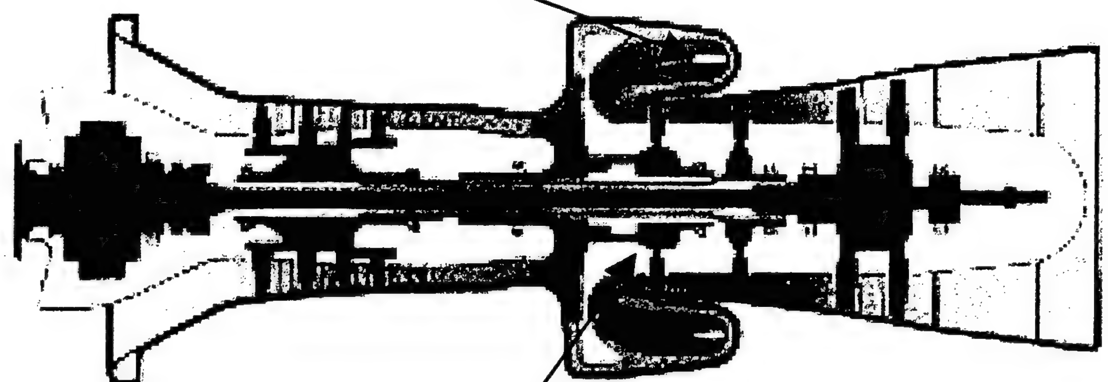
Engine Applications

Fuel-air mixing

- Improve stability - lean blowout
- Optimize off-design performance
- Reduce emissions



Turbine inlet temperature profile

- Increase engine lifetime

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Approach

Traditional mixing control in free shear flows

- Accomplished through manipulation of large scale vortical structures
- Is *indirect* and relies on energy cascade

thus

- Mixing at the smallest scales is only *weakly* coupled to the control input

Focus of present work

Mixing Control in single and co-flowing round jets

- Direct excitation of diffusive scales
- Simultaneous control of large-scale motions (entrainment) *via* couplings within the small scales
- Spatial control

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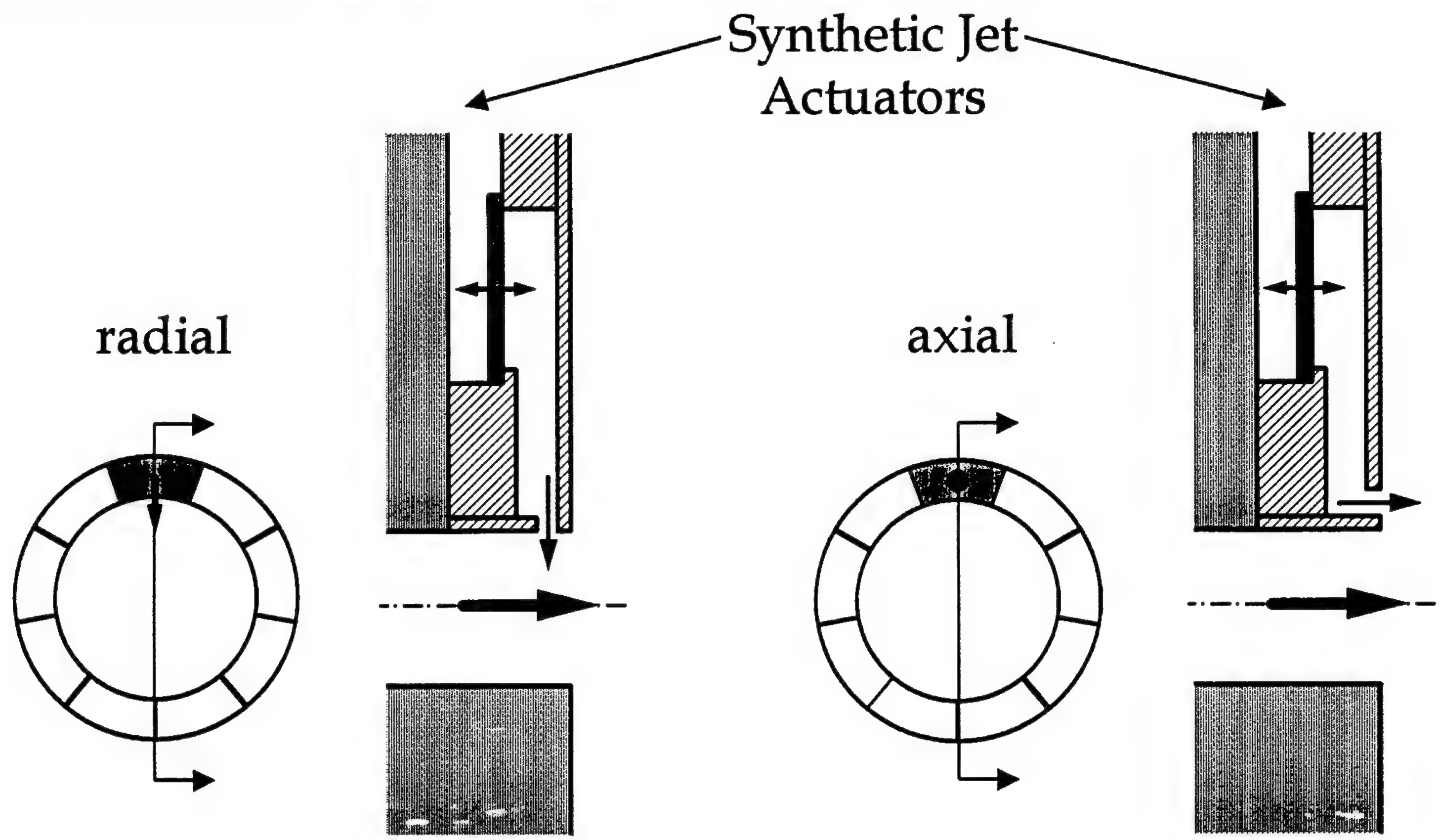
Jet Mixing Facility



D = 2.54 cm U = 11 m/s

f = 1.2 kHz Re = 1.9×10^4

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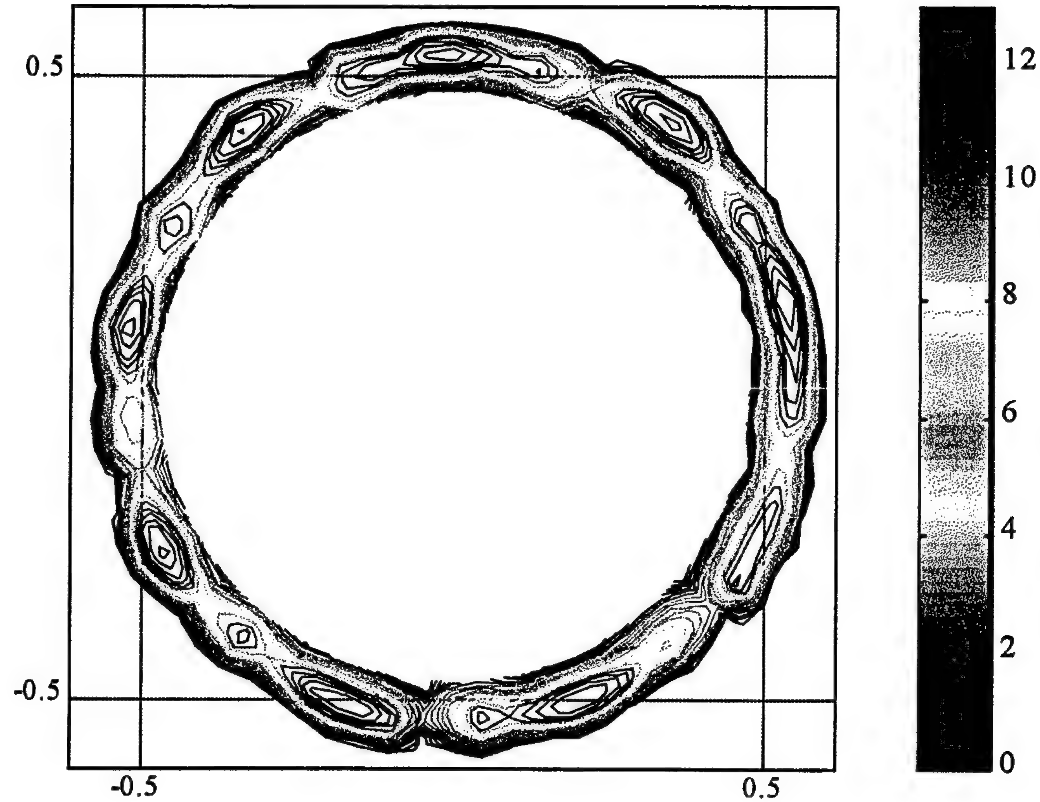
Actuator Array - Streamwise Velocity

x/D = 0.25



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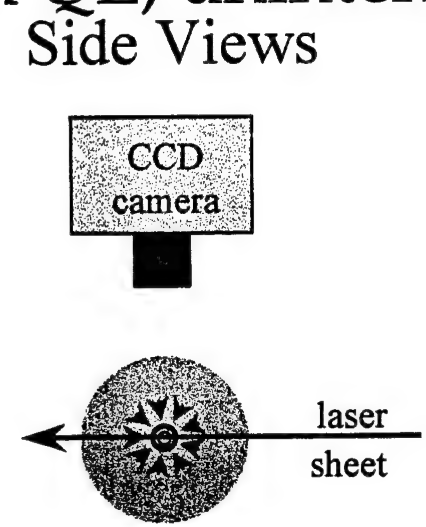
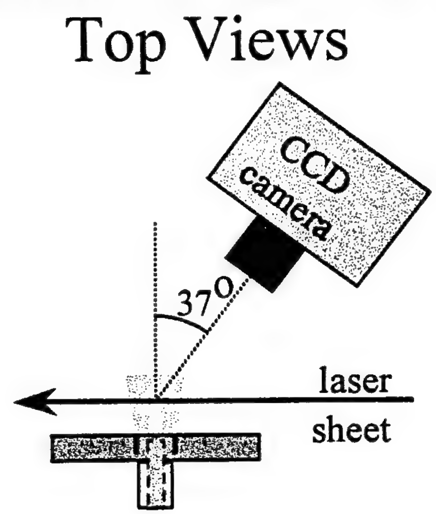
Mixing Measurements using Acetone PLIF

- Measures average concentration per pixel
- Linear with concentration and laser power
- Wide dynamic range
  - Strong signal (acetone)

coupled with

  - High QE, unintensified CCD camera





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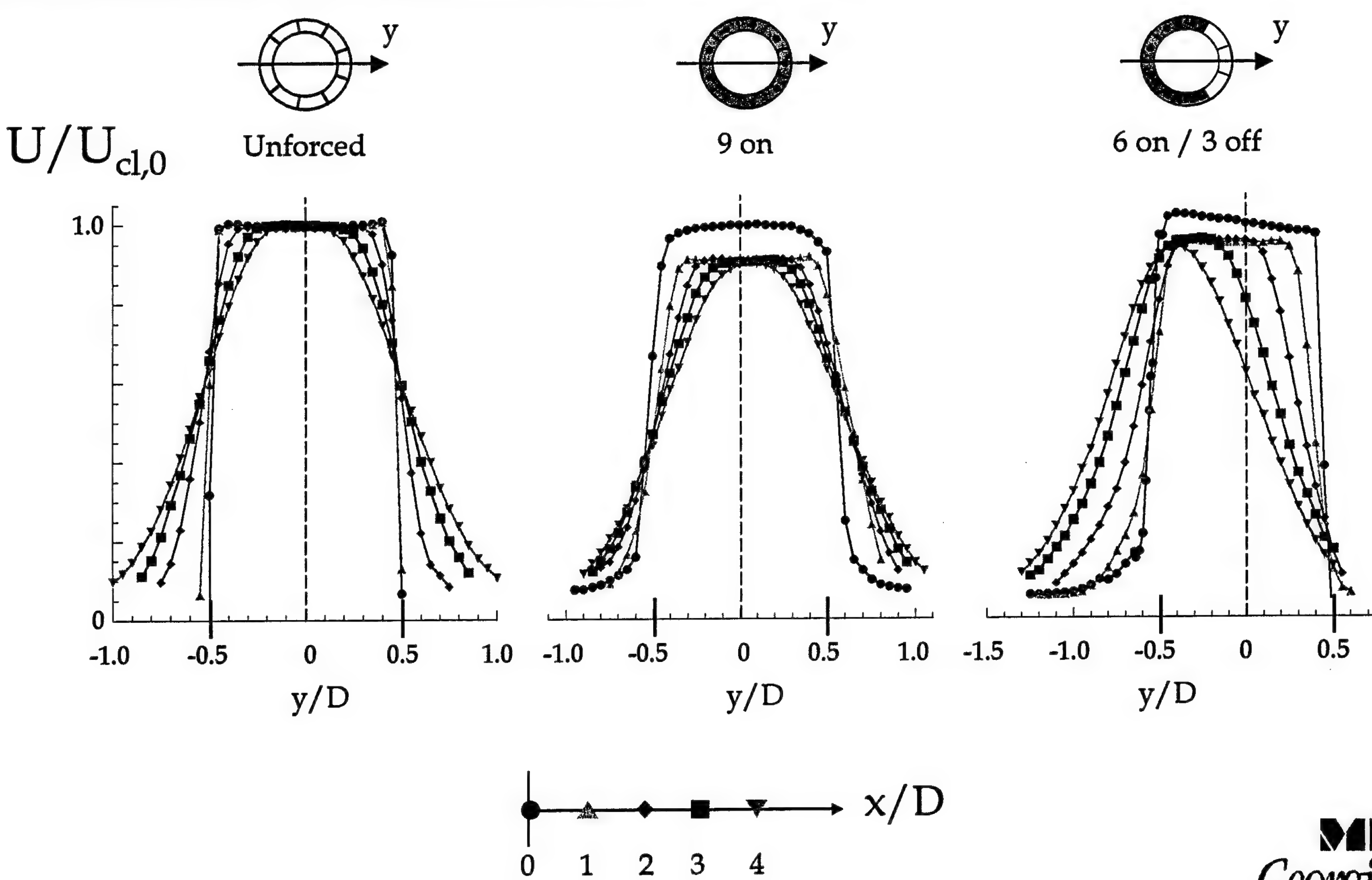
Single Jet: Mean Streamwise Velocity



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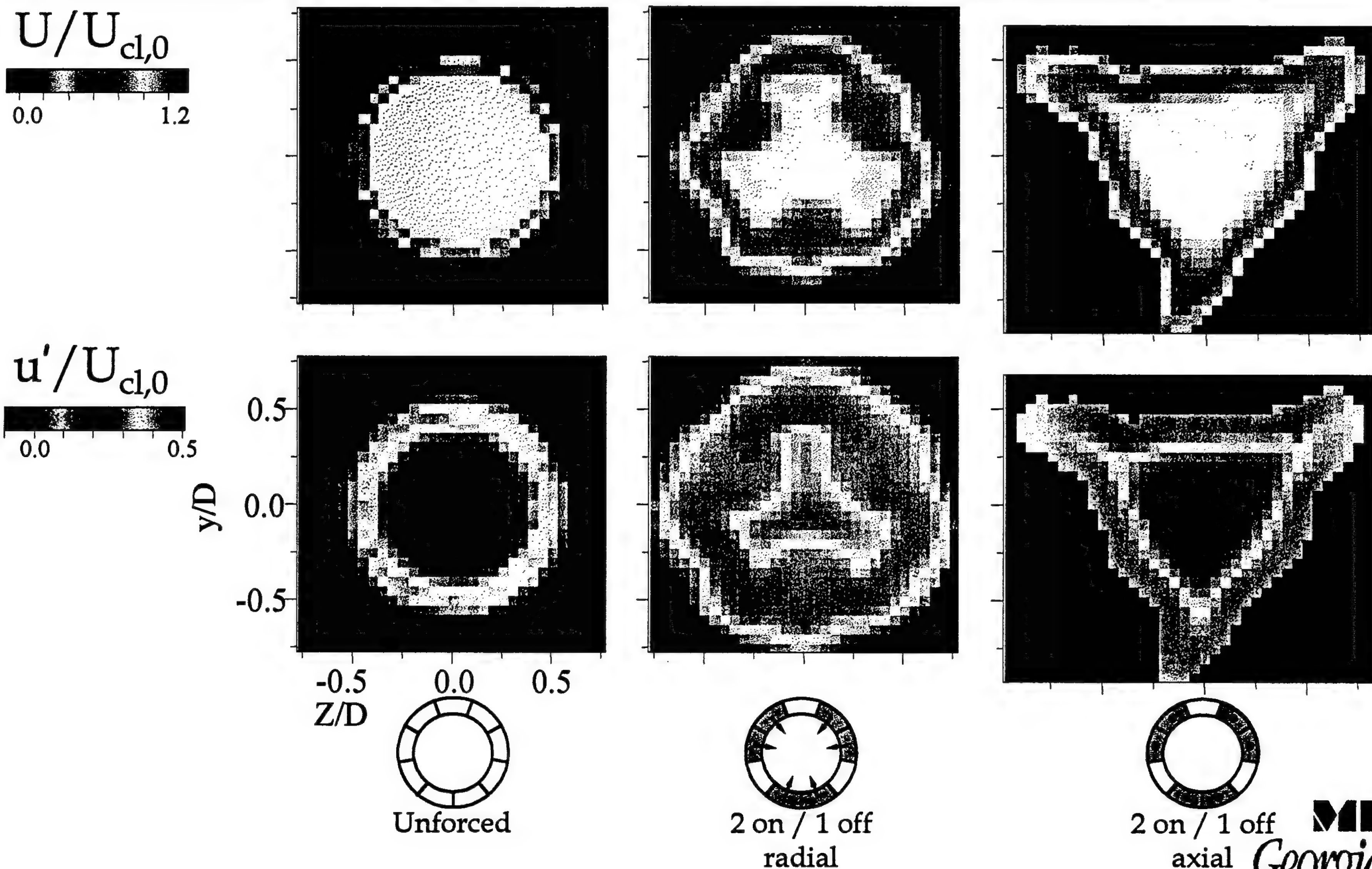
Single Jet, Spatially Modulated: Streamwise Velocity, x/D = 1



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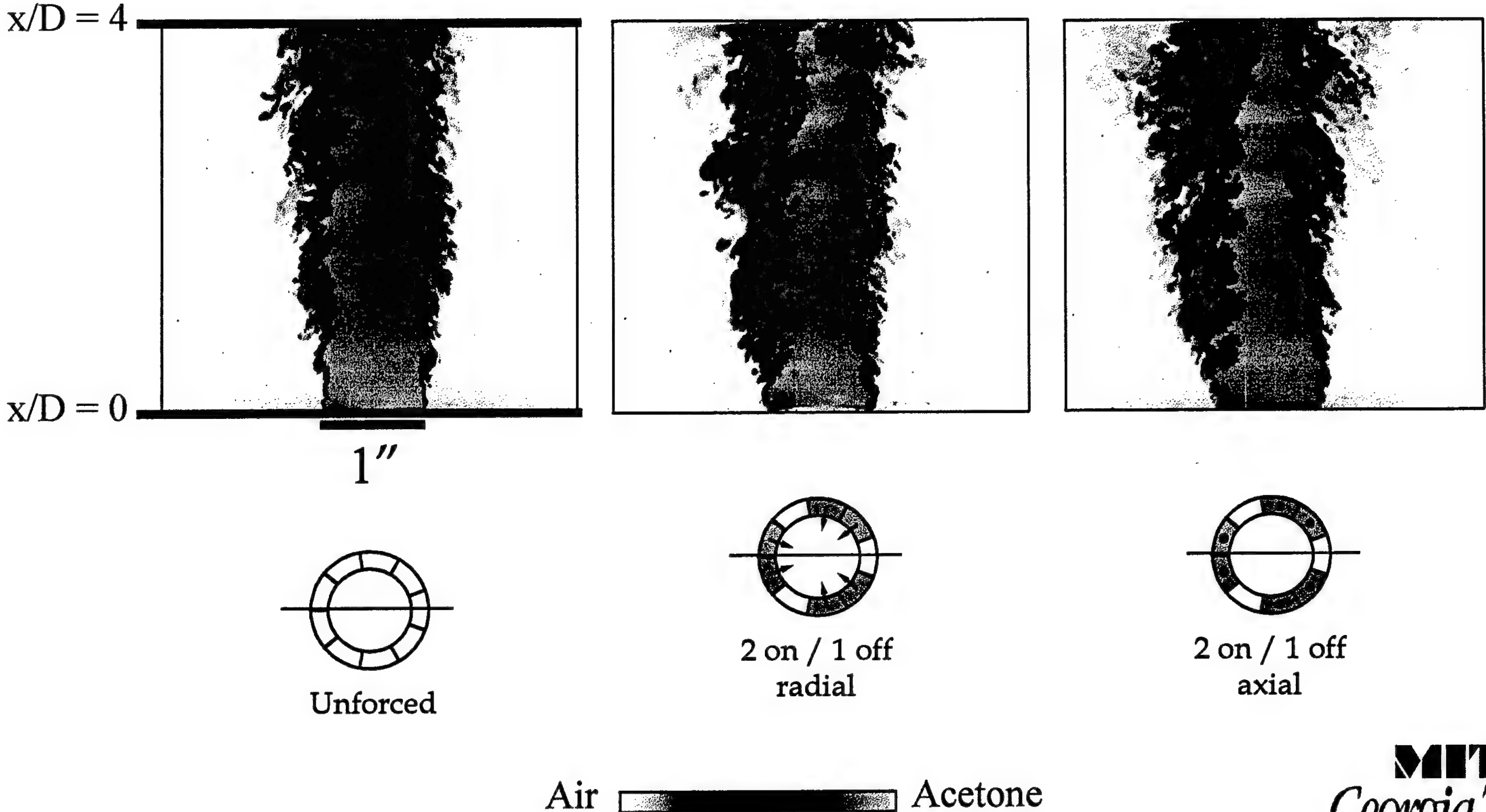
Single Jet: PLIF Acetone Mixing



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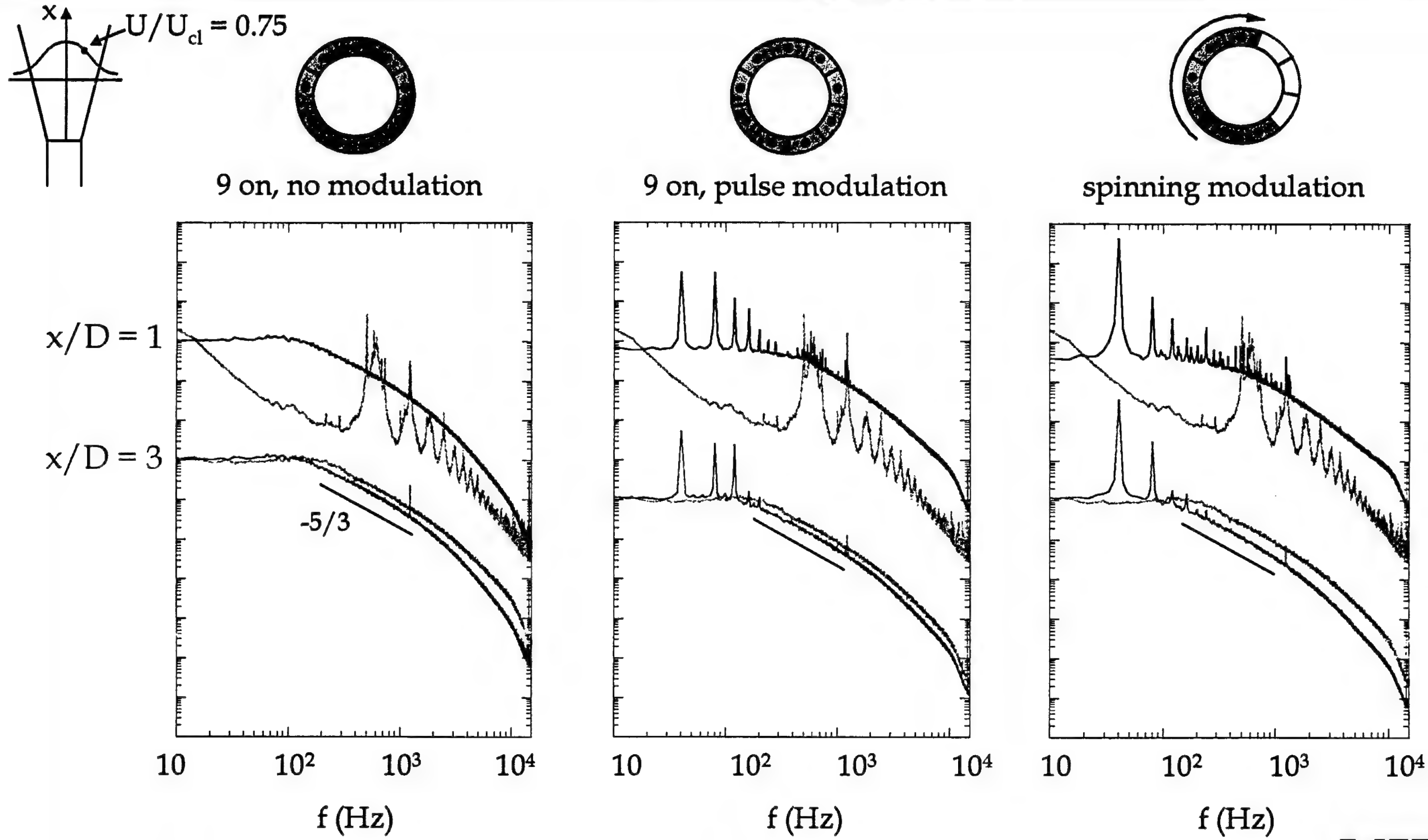
Single Jet: Amplitude Modulated Excitation



- Spatial and Temporal Modulation

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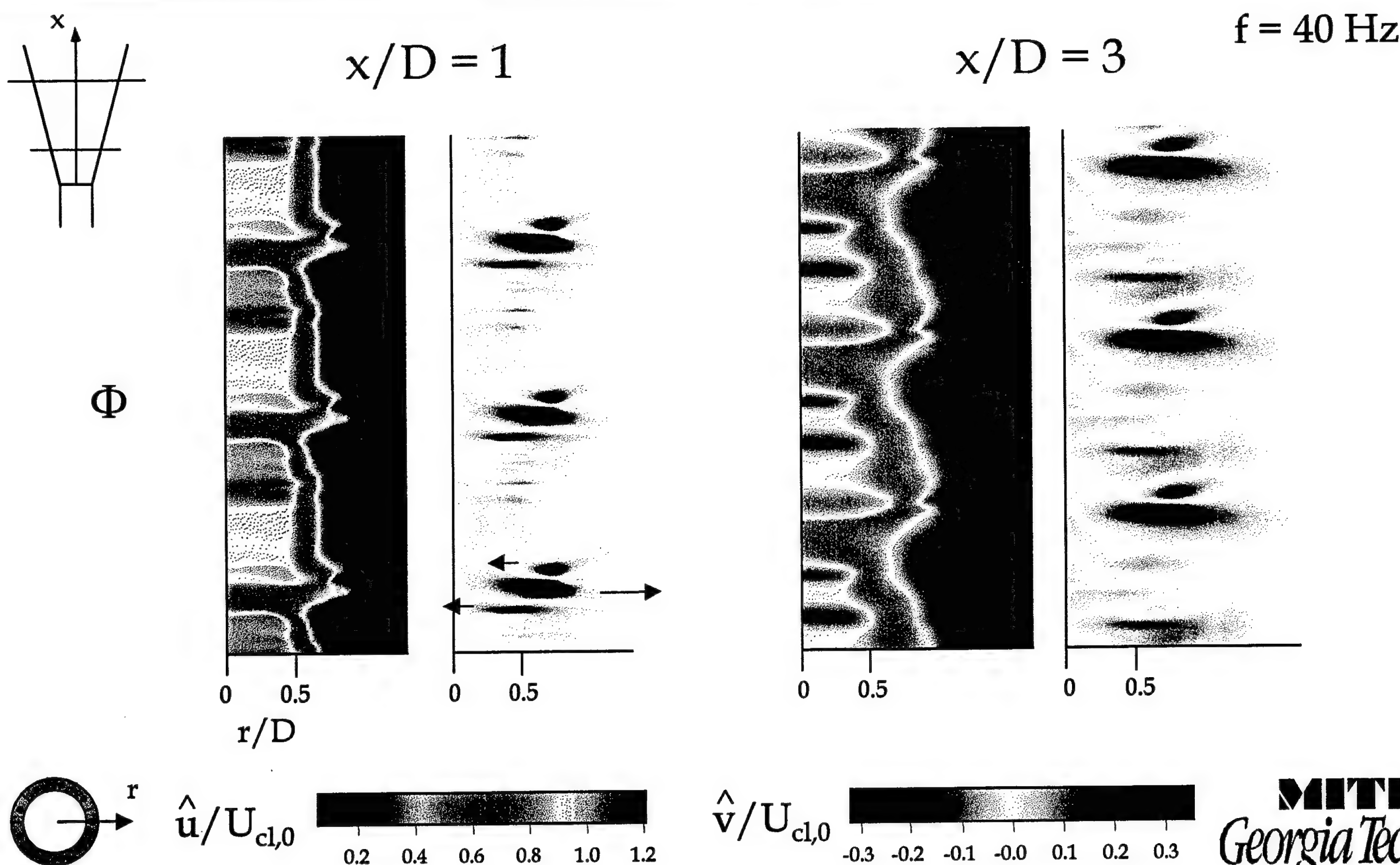
Single Jet, Pulsed Modulation: Phase Averaged Velocity



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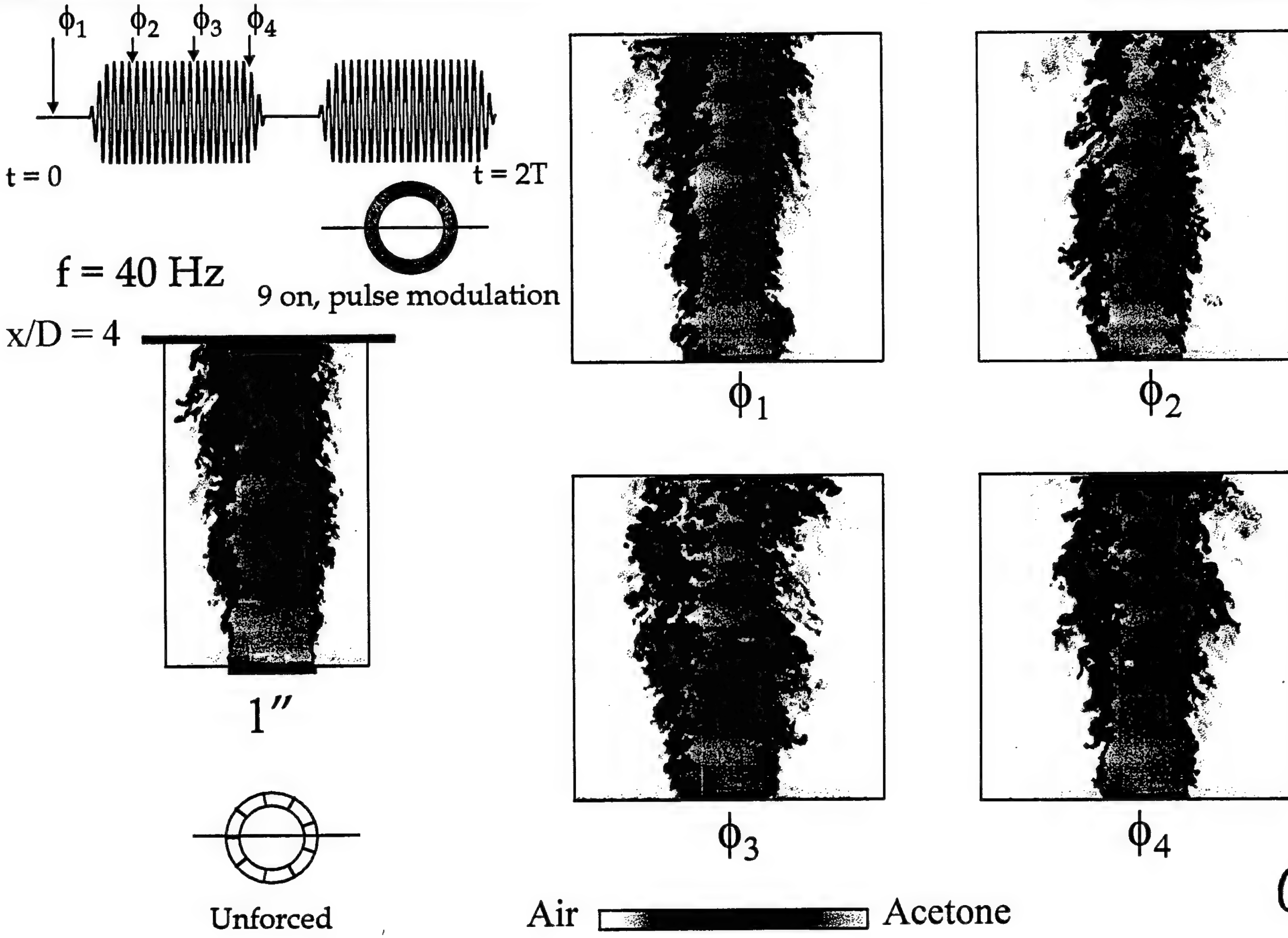
Single Jet, Pulsed Modulation: Streamwise Mixing



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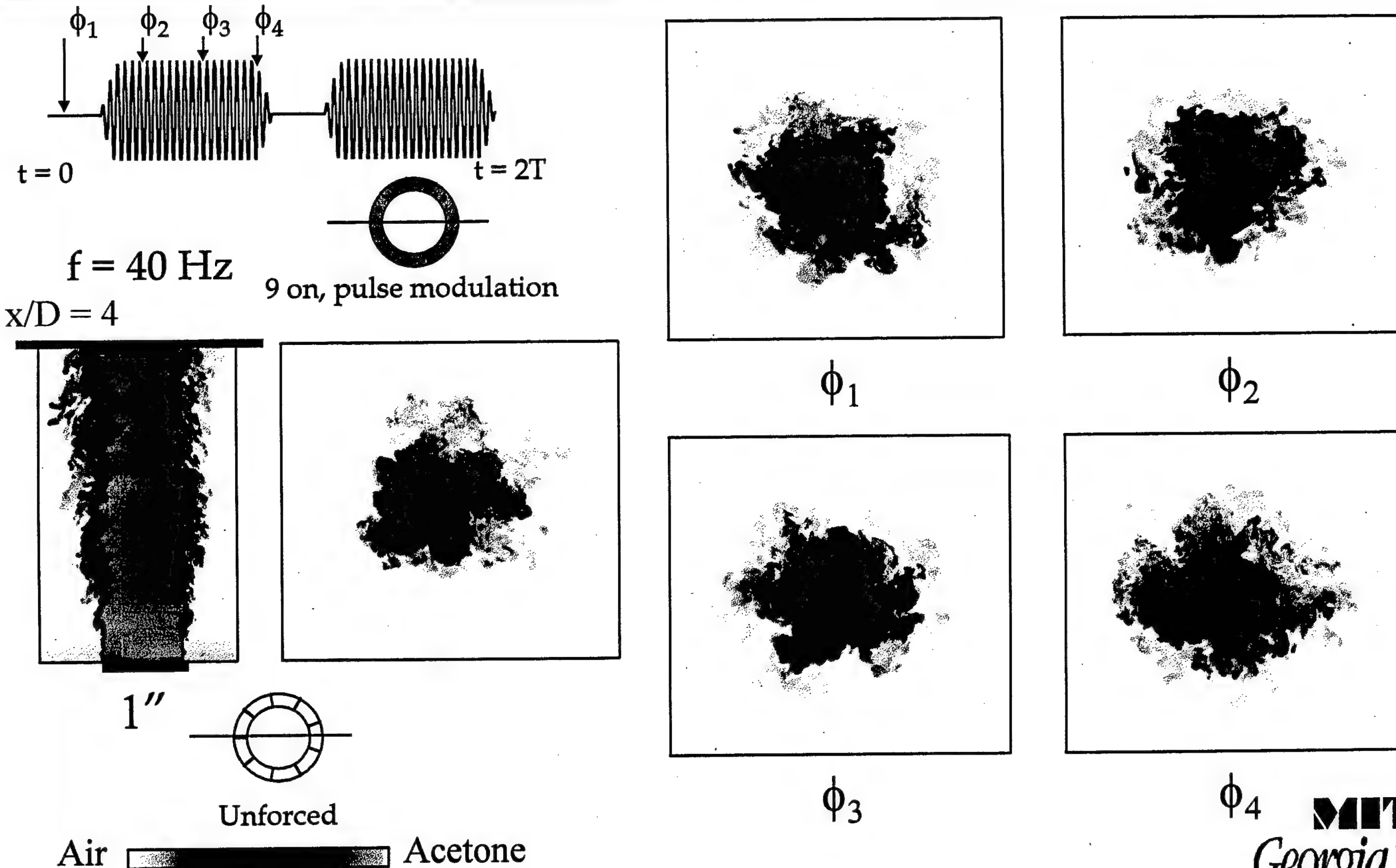
Single Jet, Pulsed Modulation: Cross-stream Mixing



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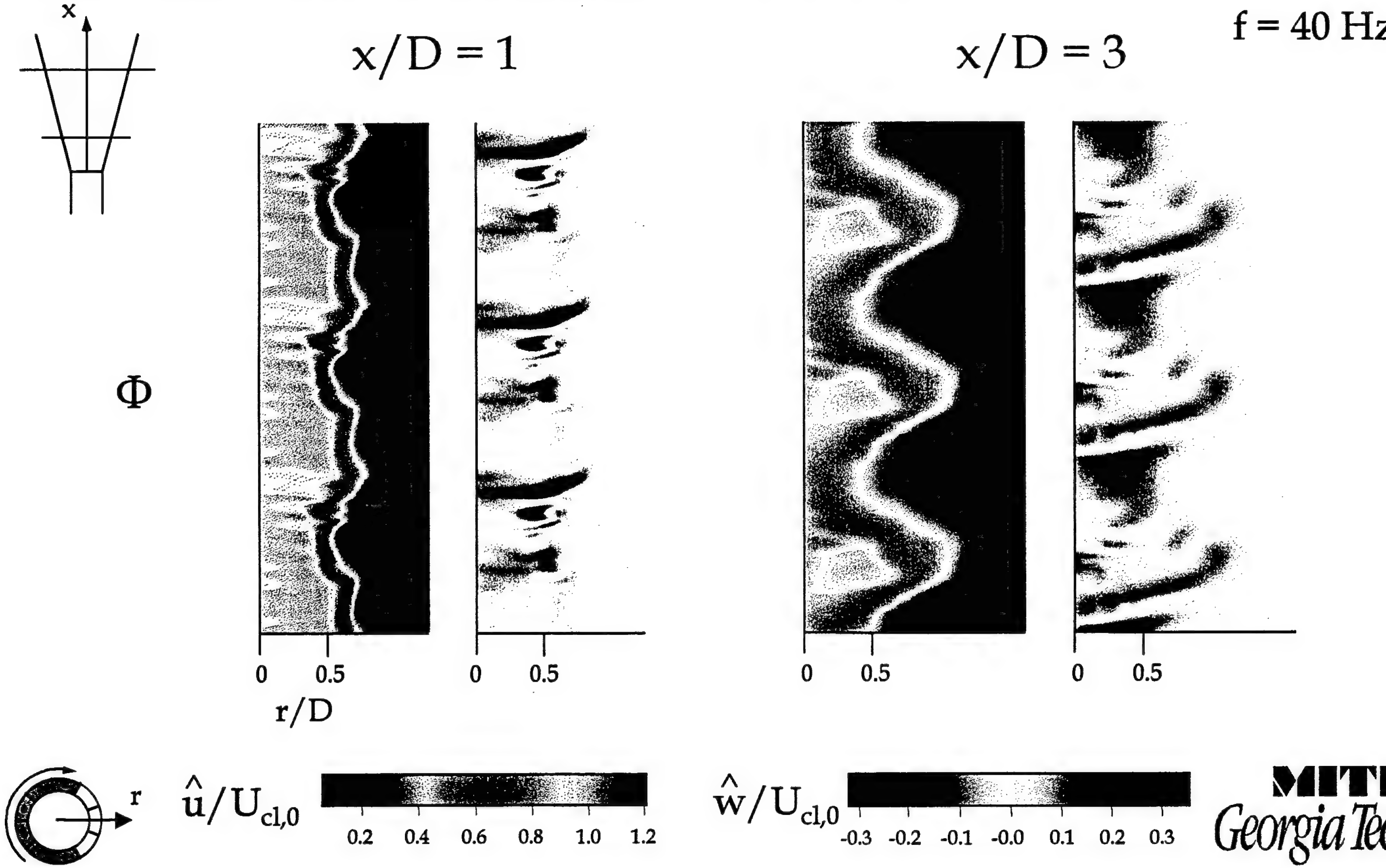
Single Jet, Spinning Modulation: Phase Averaged Velocity



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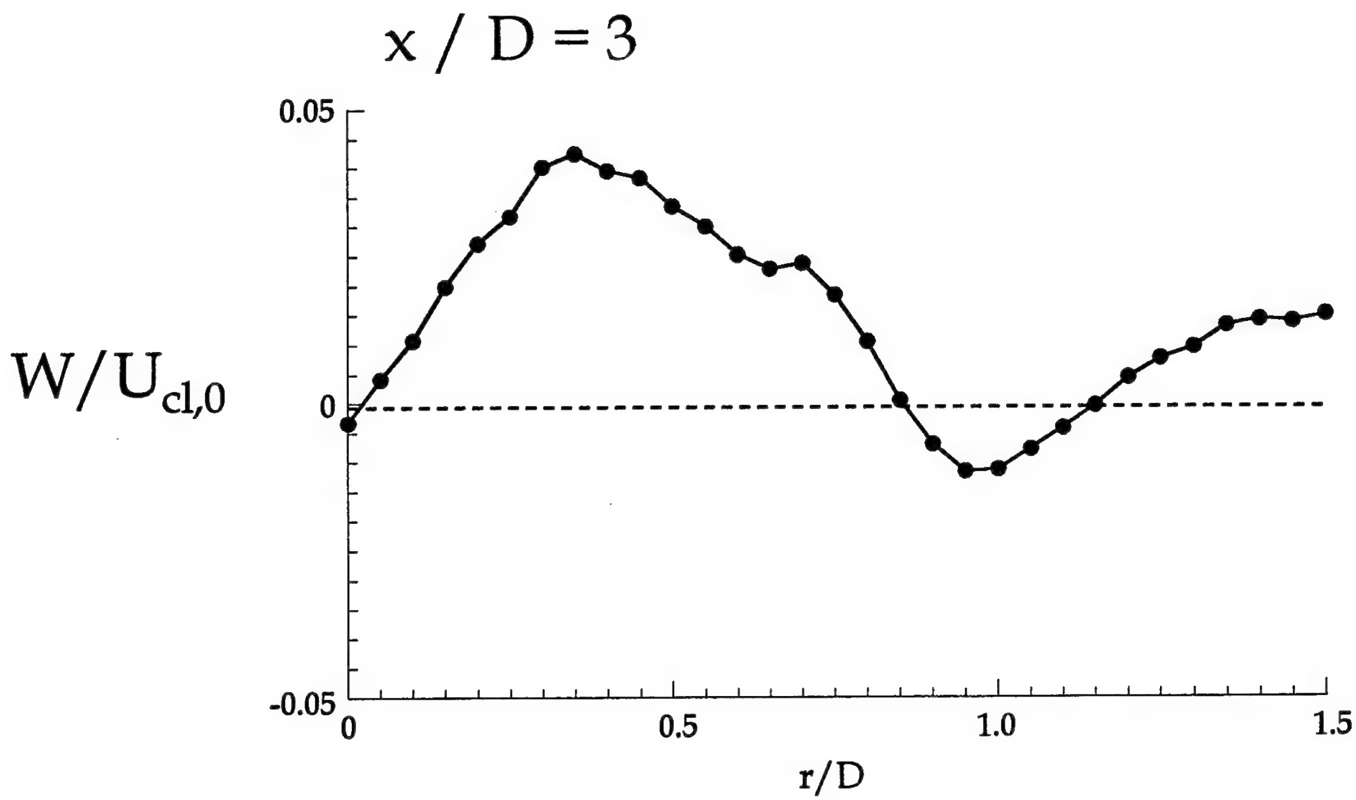
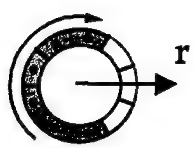
Single Jet, Spinning Modulation: Swirl



x/D	Sw
1	0.0143
2	0.0033
3	0.0336
4	0.0730



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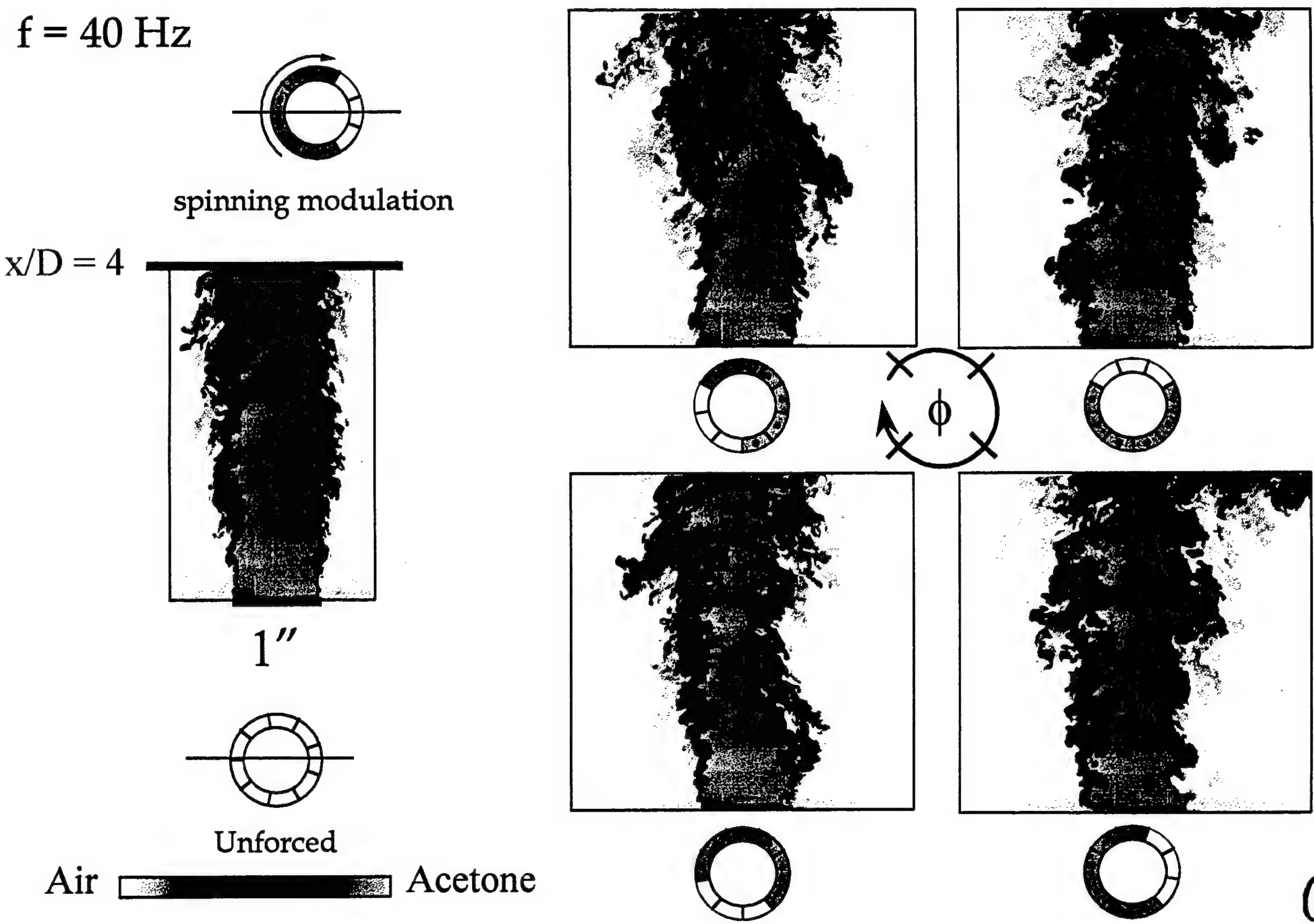
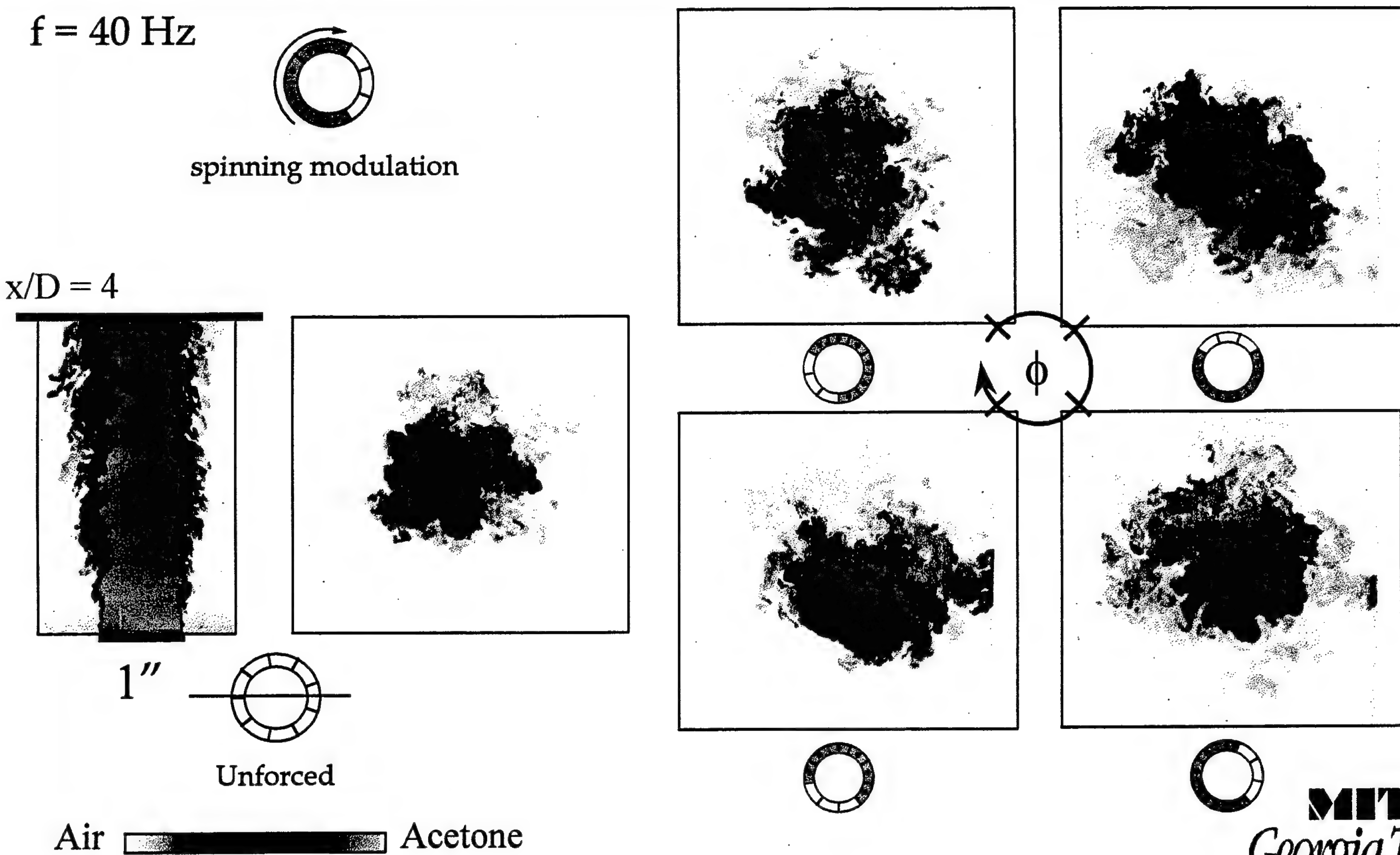
Single Jet, Spinning Modulation: Streamwise Mixing



Single Jet, Spinning Modulation: Cross-stream Mixing



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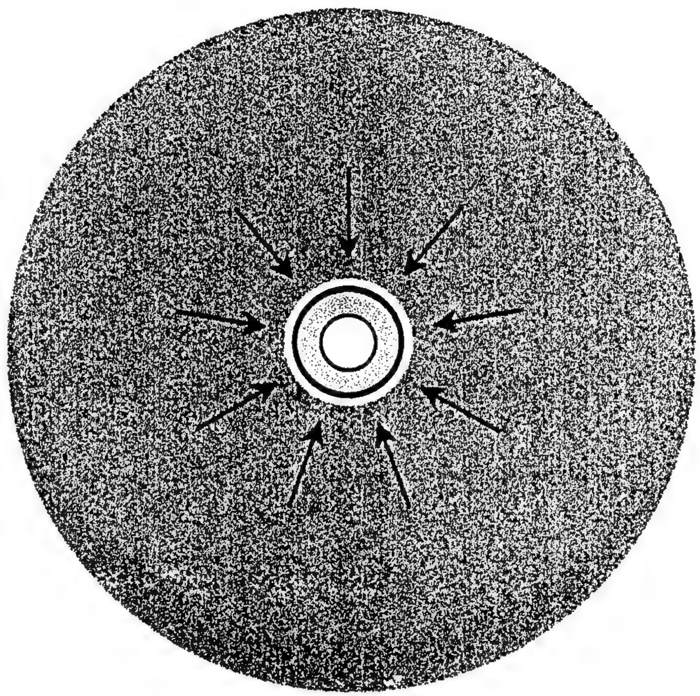
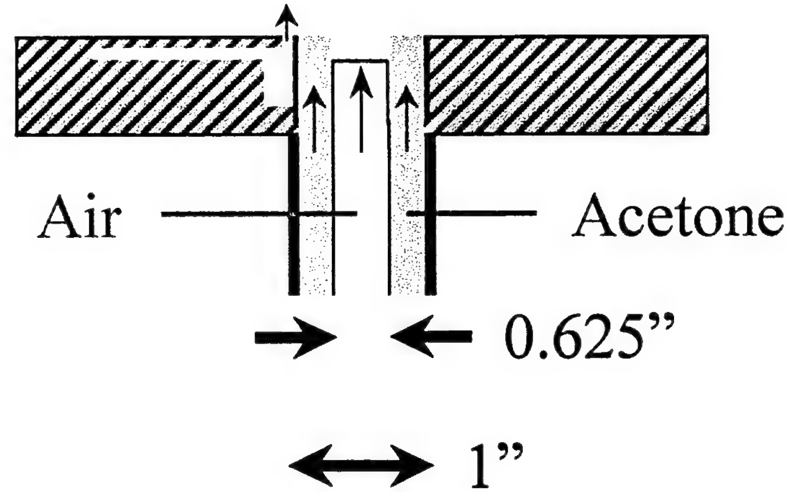
Co-Flowing Jets: Facility





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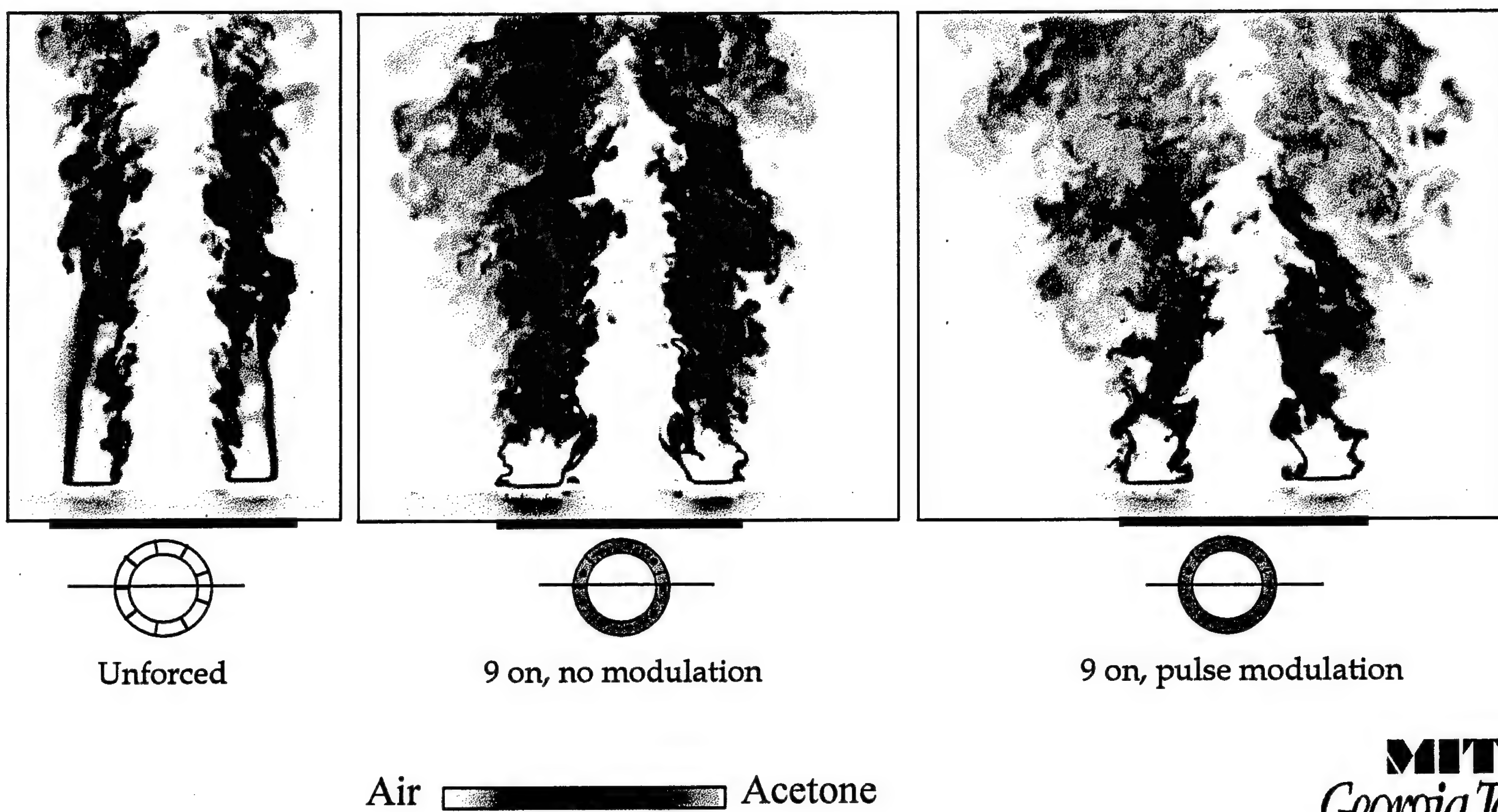
Co-Flowing Jets, Symmetric Forcing: Streamwise Mixing



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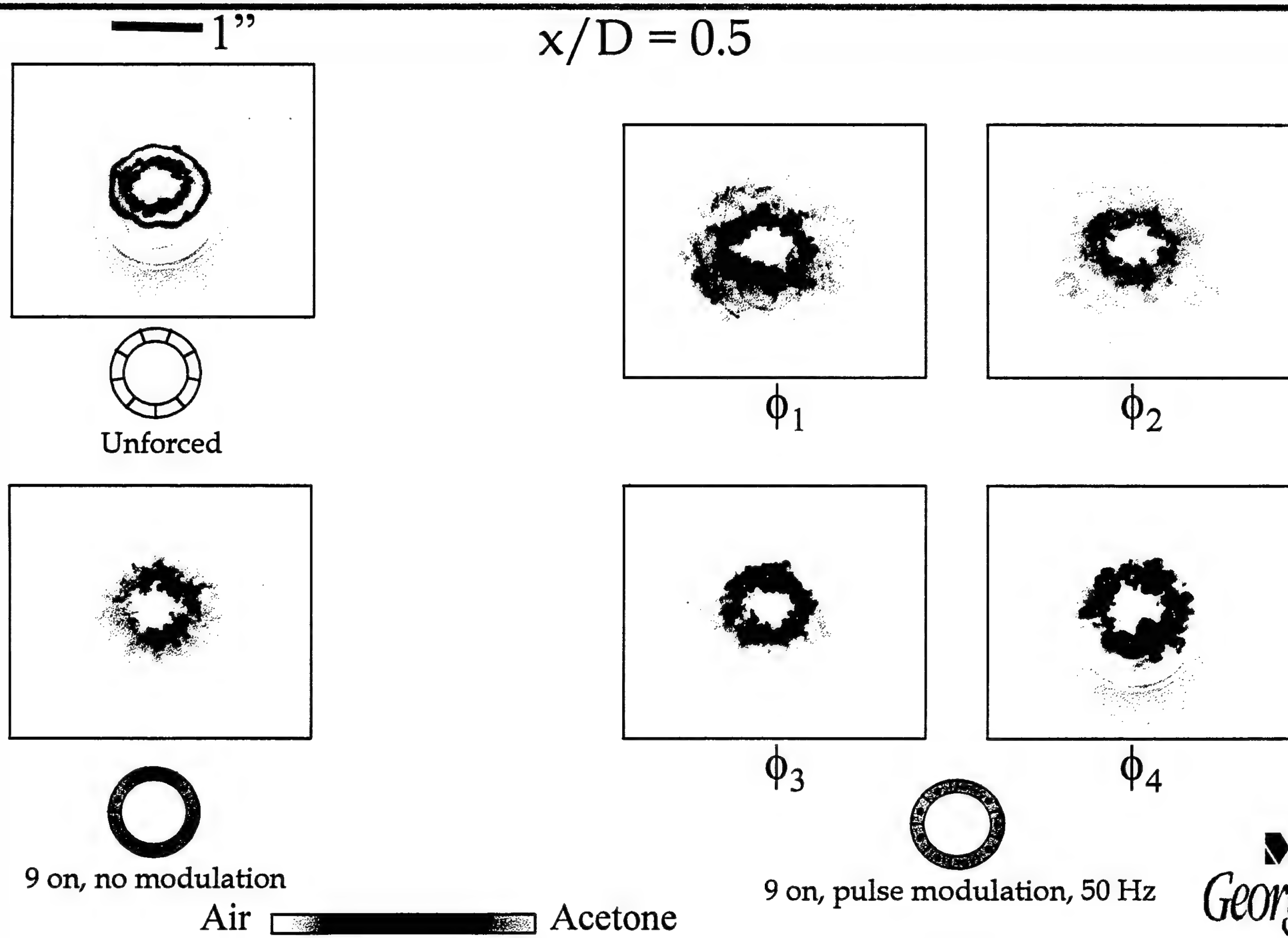
Co-Flowing Jets, Symmetric Forcing: Cross-stream Mixing



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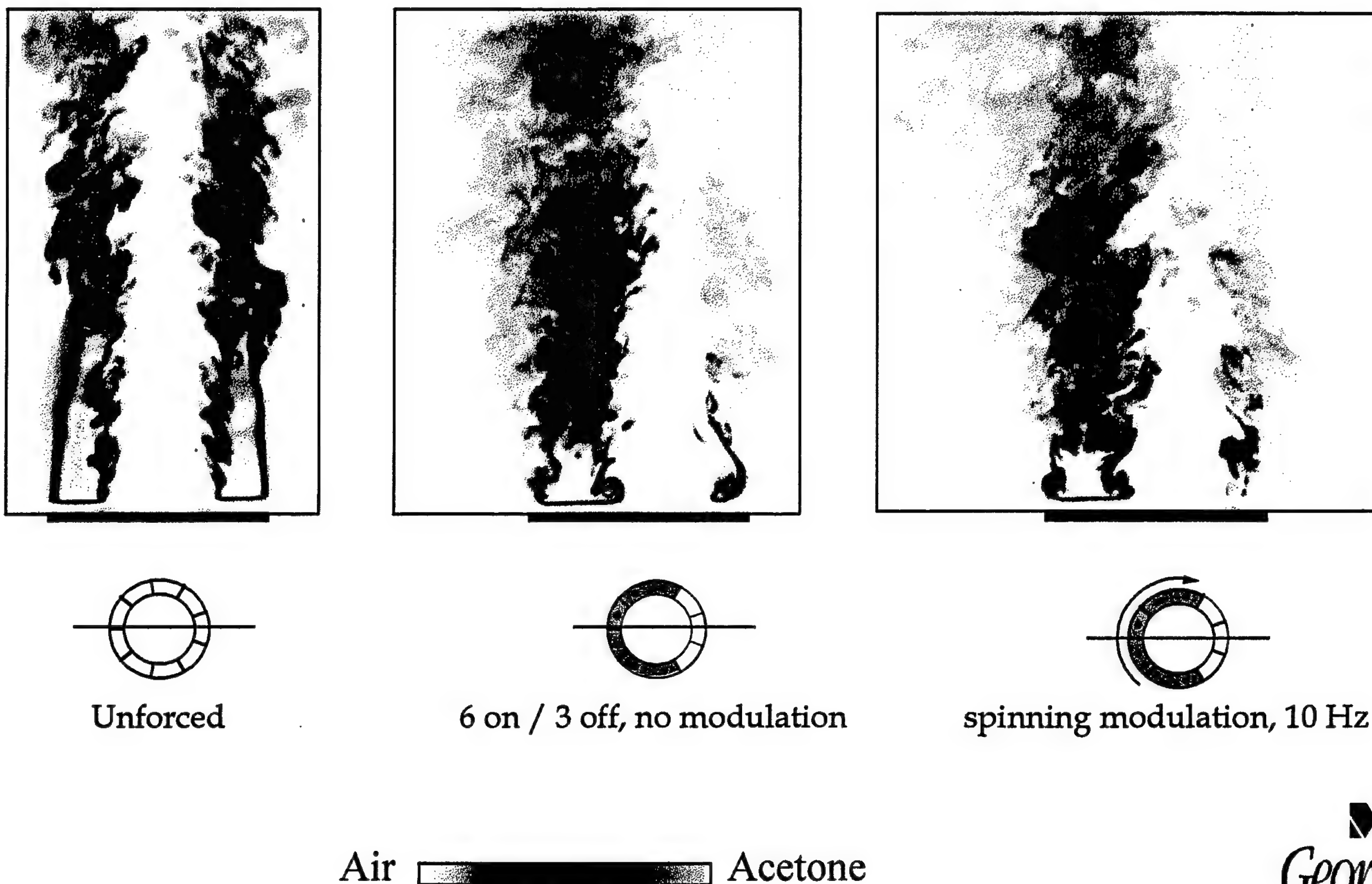
Co-Flowing Jets, Asymmetric Forcing: Streamwise Mixing



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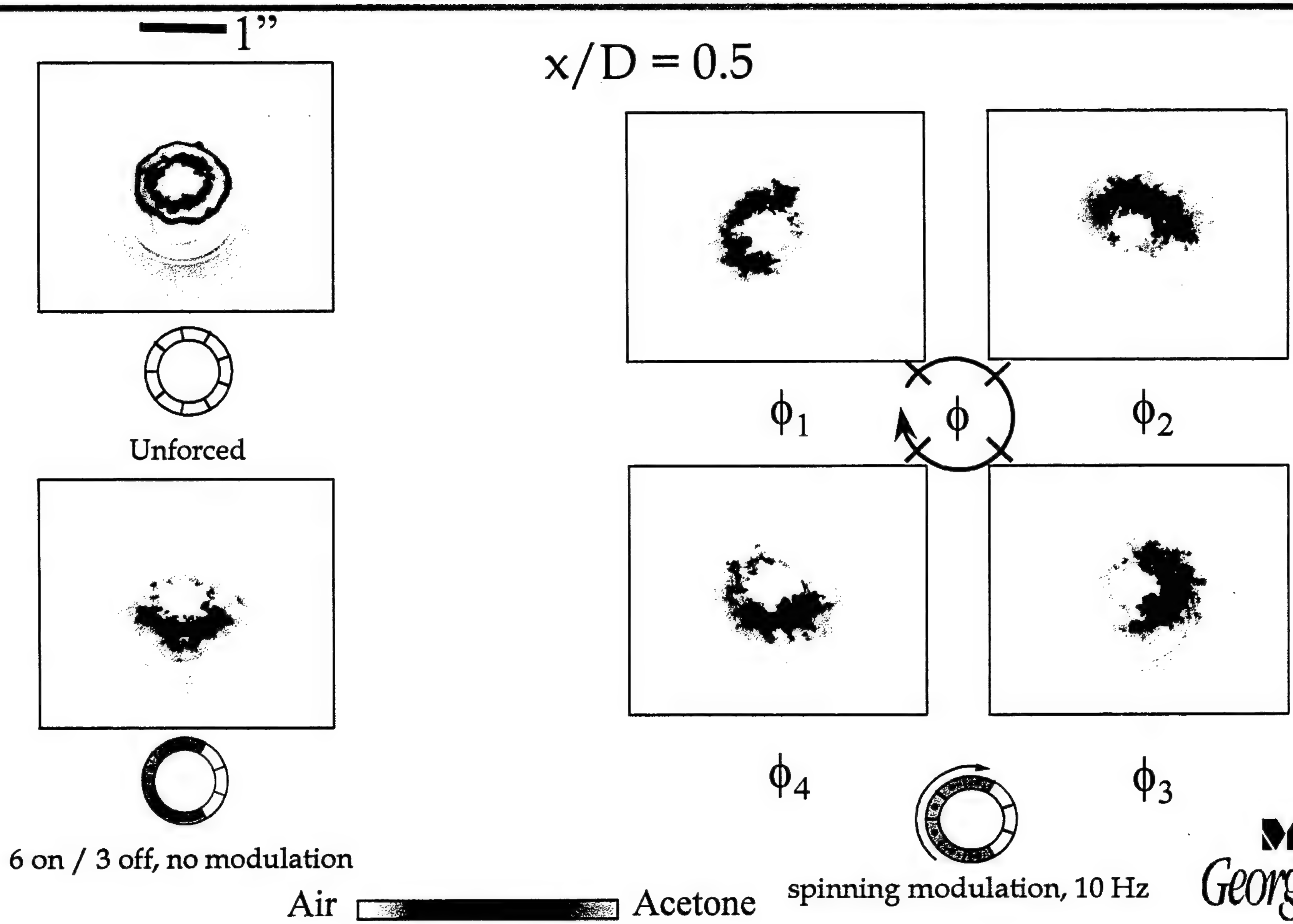
Co-Flowing Jets, Asymmetric Forcing: Cross-stream Mixing



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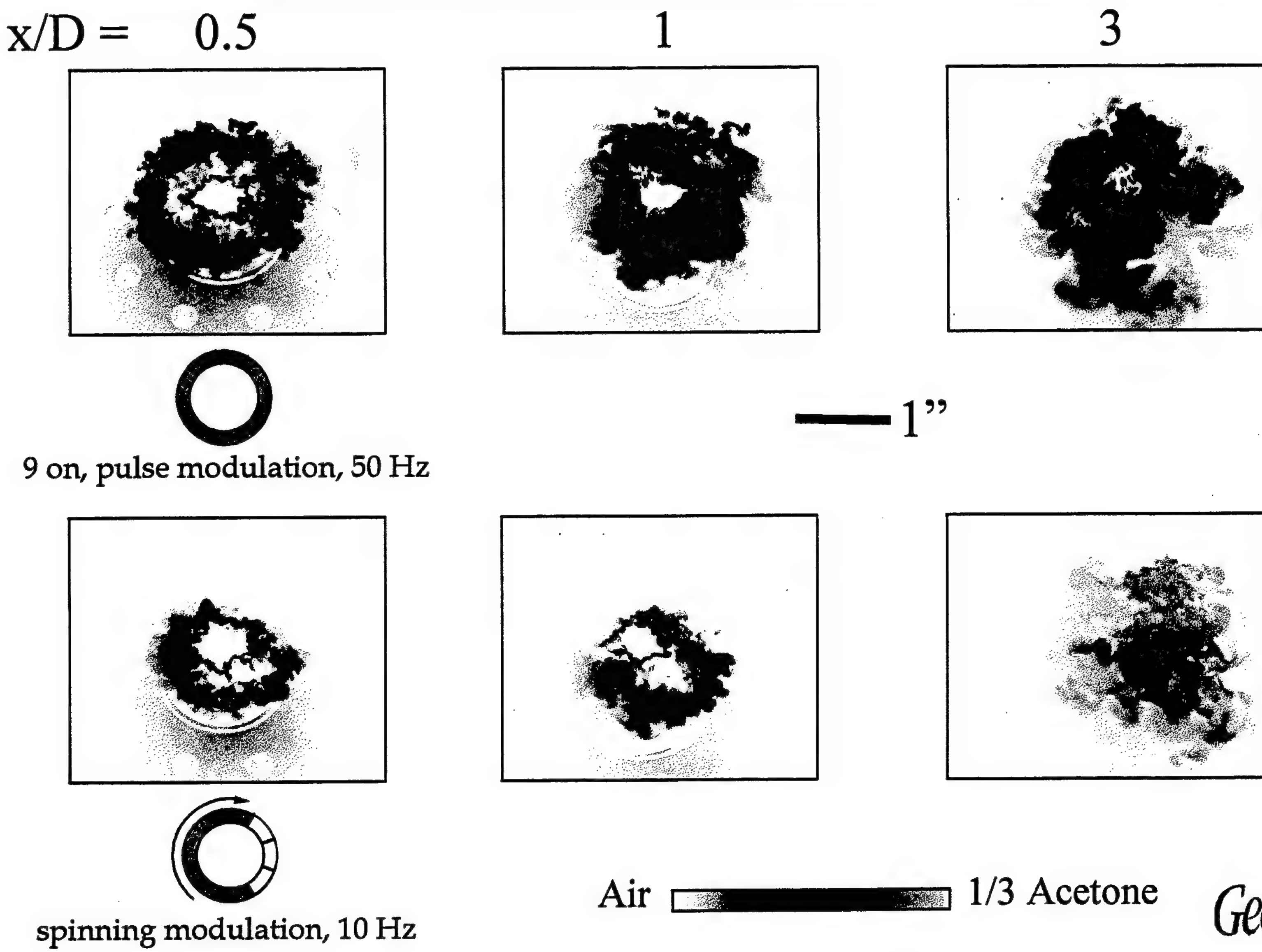
Co-Flowing Jets: Streamwise Variation



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Conclusions

- Mixing enhancement using direct small-scale excitation is demonstrated in single and co-flowing axisymmetric jets
- Flow modification using radial and axial excitation modes is demonstrated
  - Amplitude modulation of the excitation frequency results in controllable large-scale flow structures
  - Introduction of azimuthal modes leads to jet swirl
- Mixing control
  - Controlled jet spreading and mixing rate
  - Large-scale entrainment
  - Circumferential distribution

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MEMS Devices for High Temperature Applications

Jennifer English and Mark G. Allen

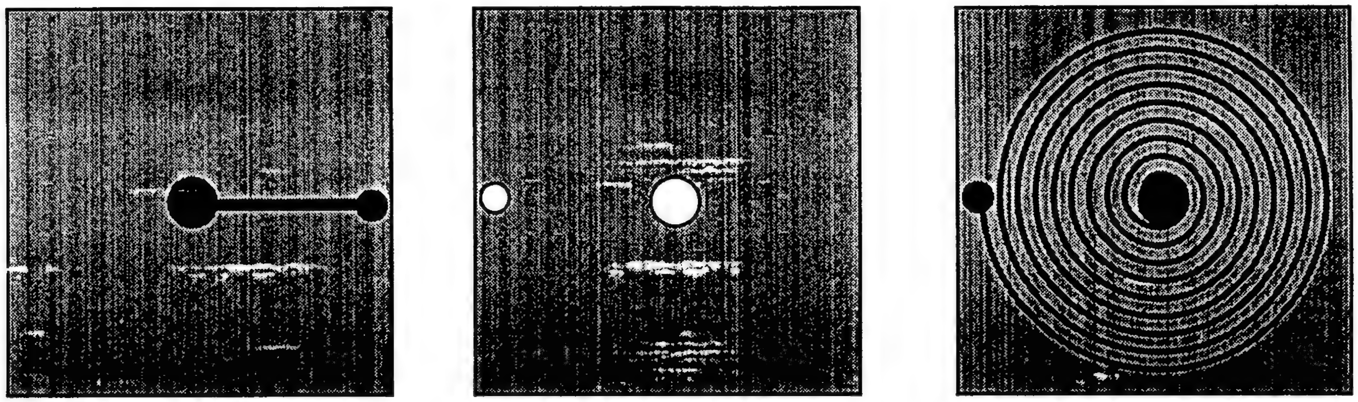
Project Review

- Design and fabricate a high temperature pressure sensor.
  - Ceramic tape and high temperature metals.
  - Wireless Scheme: Pressure sensitive capacitor and fixed inductor.
  - Monitor resonant frequency to determine pressure.
- Testing and data retrieval.
  - Remote readout: Impedance meter, oscillator tank circuits, transmitting and receiving antennae.
  - Interrogation of arrays to monitor several local pressures simultaneously.

Last Year's Objectives and Issues

- Fabricate the LC design of ceramic pressure sensor.
- Enhance sensitivity of pressure sensors.
  - Increase pressure sensitivity.
  - Decrease temperature sensitivity.
- Design and test remote readout system for data retrieval.
  - Wireless and passive system.
  - Single sensor and array interrogation.
- Test sensor at elevated temperatures.
- Begin investigation into health monitoring devices.

Micromachined Ceramic Pressure Sensor Fabrication

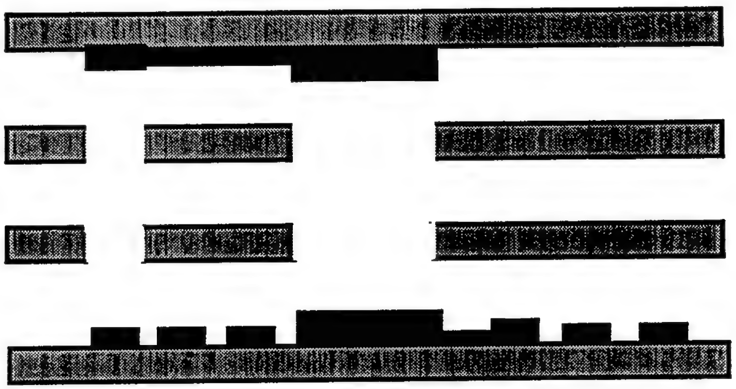


Fabrication Procedure

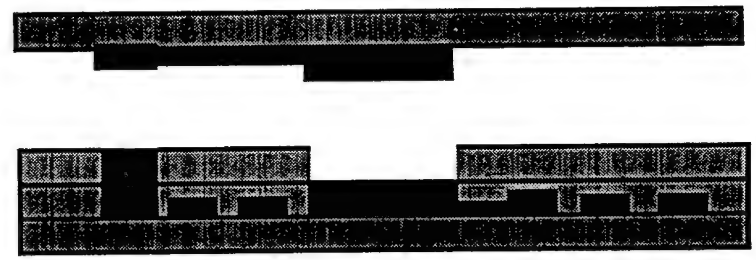
- Cut layers from ceramic tape.
- Punch via holes.
- Print metal patterns for capacitor electrodes and inductor coil.

Micromachined Ceramic Pressure Sensor Fabrication

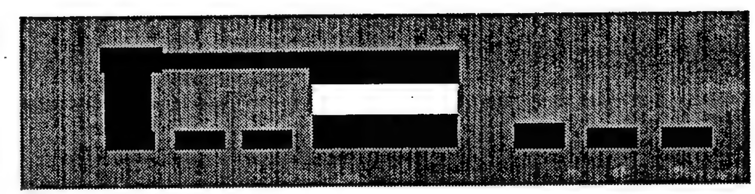
Alignment of Layers



Via Filling



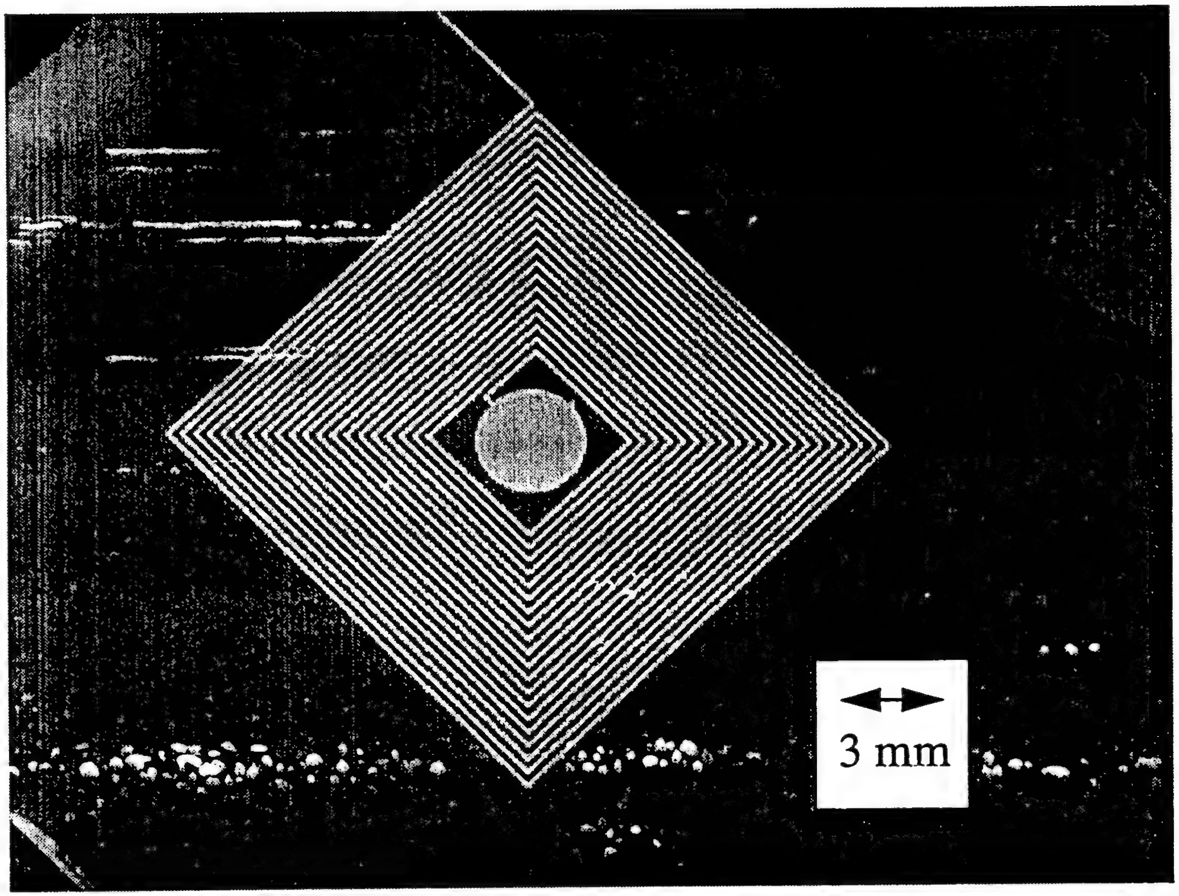
Lamination and Curing



Fabrication Procedure

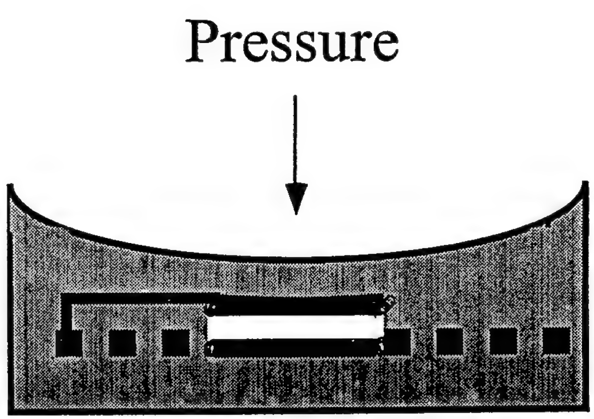
- Align layers.
- Fill vias with metal paste.
- Laminate: 3000psi 10min.
- Fire: 850°C 1 hr

Ceramic Micromachined Pressure Sensor



LC Ceramic Pressure Sensor Design

- Design Criteria
  - Pressure range (1- 50 atm).
  - Frequency spectrum (1MHz - 1GHz).
  - Capacitor electrode size (≤ 1cm).
  - Inductor (geometry and quality factor).



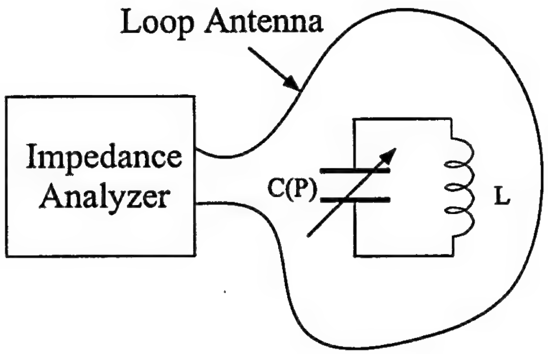
$$C(P) = \frac{\varepsilon A}{d(P)}$$

$$f_o(P) = \frac{1}{2\pi\sqrt{L * C(P)}}$$

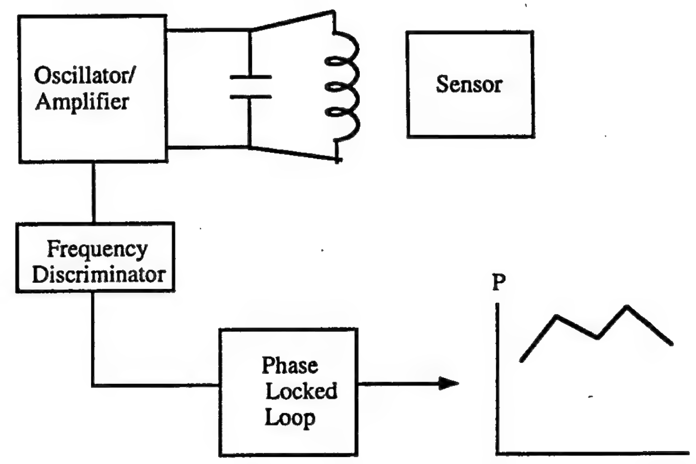
Remote Readout

- Methods for wireless data retrieval.
  - Impedance meter.
  - Oscillator with a tank circuit.
  - Transmitting/receiving antennae.

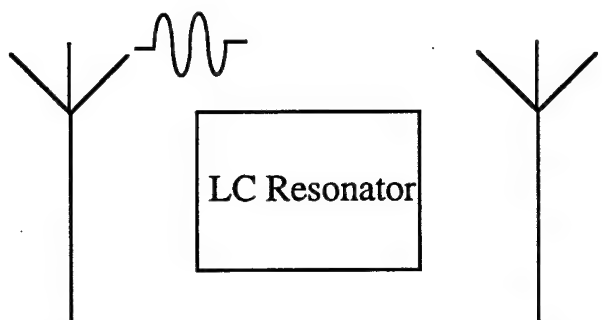
Remote Readout



Impedance Meter



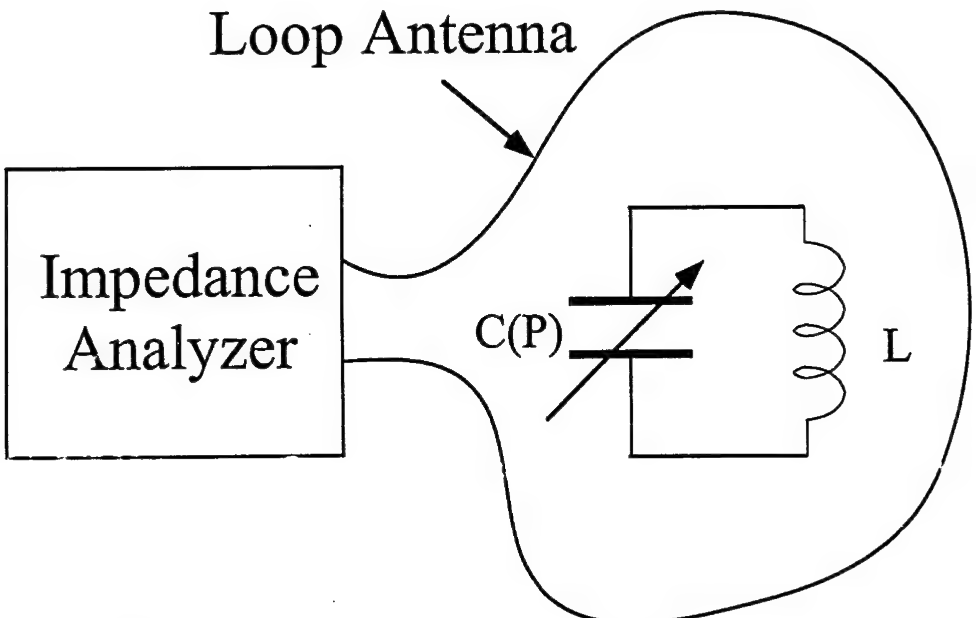
Oscillator with Tank Circuit

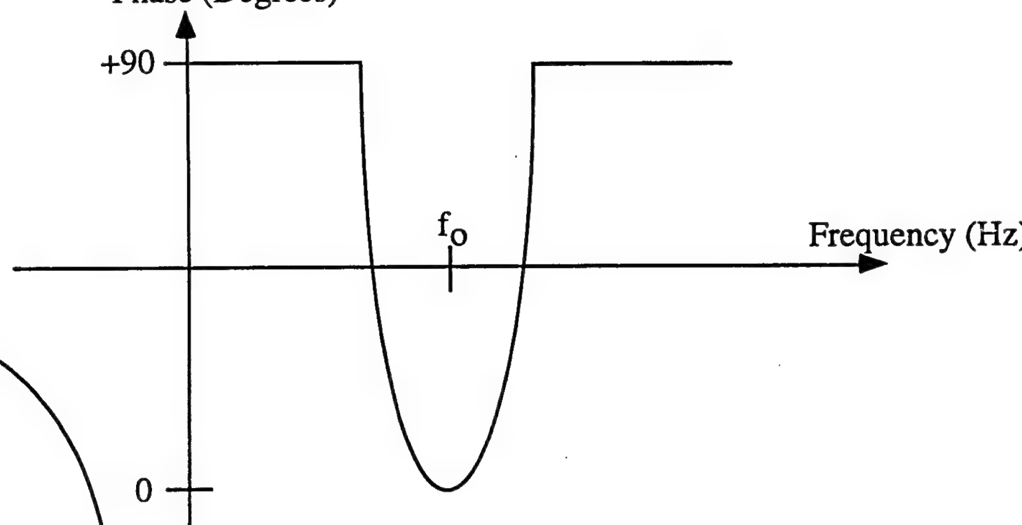


Trans./Rec. Antennae

Remote Readout

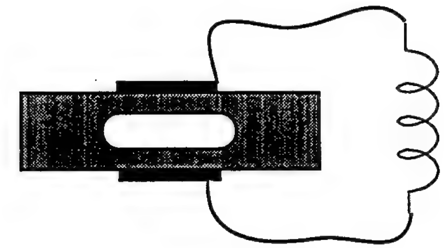
- Impedance Meter.
  - Coupling between sensor coil and loop antenna.



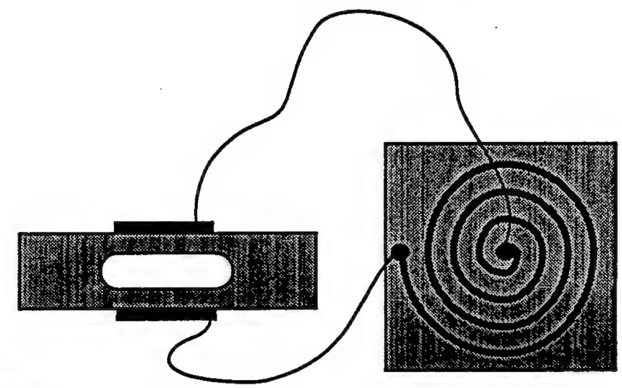


Current Work

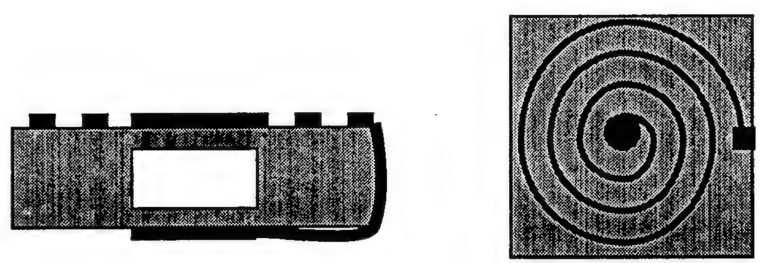
- Ceramic pressure sensor and hybrid inductor.



- Ceramic pressure sensor and printed coil on ceramic.



- Integrated ceramic pressure sensor with inductor coil.



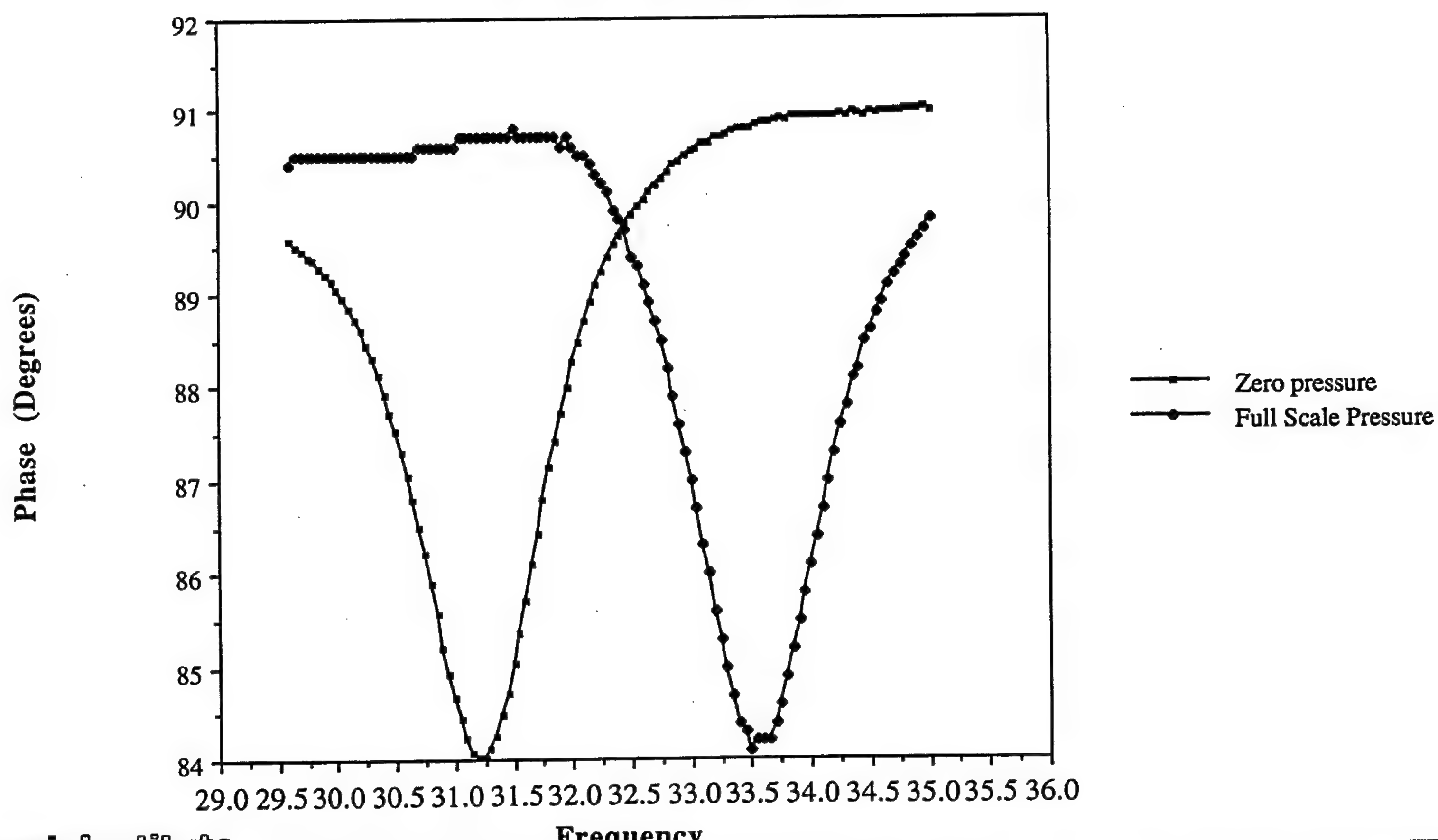
Cross Section   Top View

Experiments

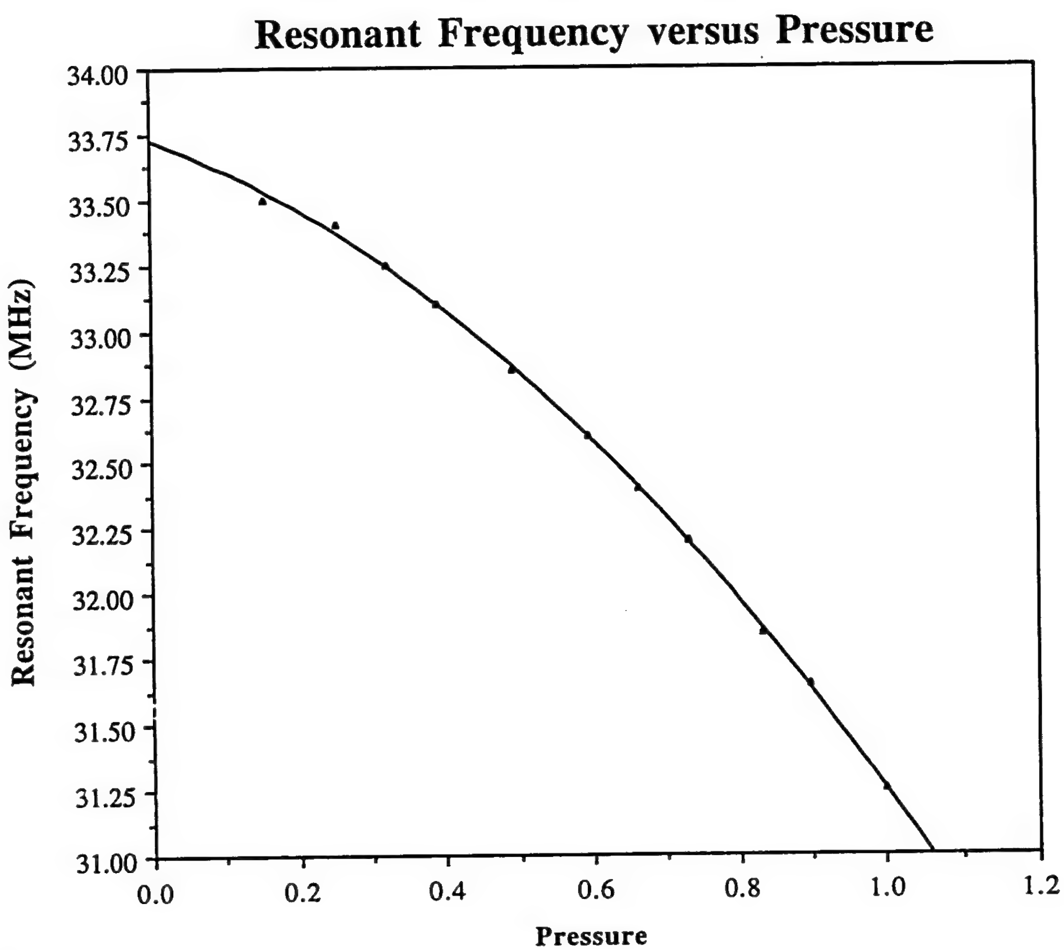
- Measure resonant frequency as a function of pressure for a single pressure sensor.
- Measure phase as a function of frequency and pressure for an array (3) sensors.
- Measure resonant frequency as a function of pressure at T= 200°C for a single sensor.

Results

Phase versus Frequency for Zero and Full-Scale Pressure



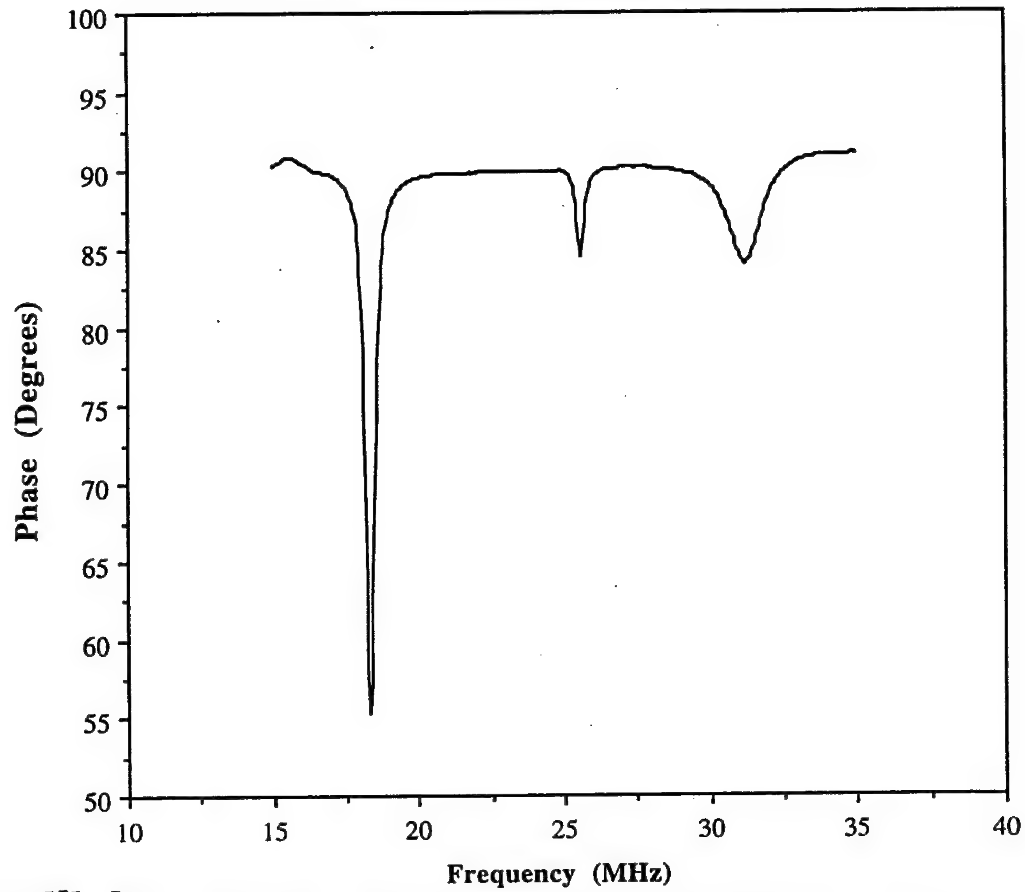
Results



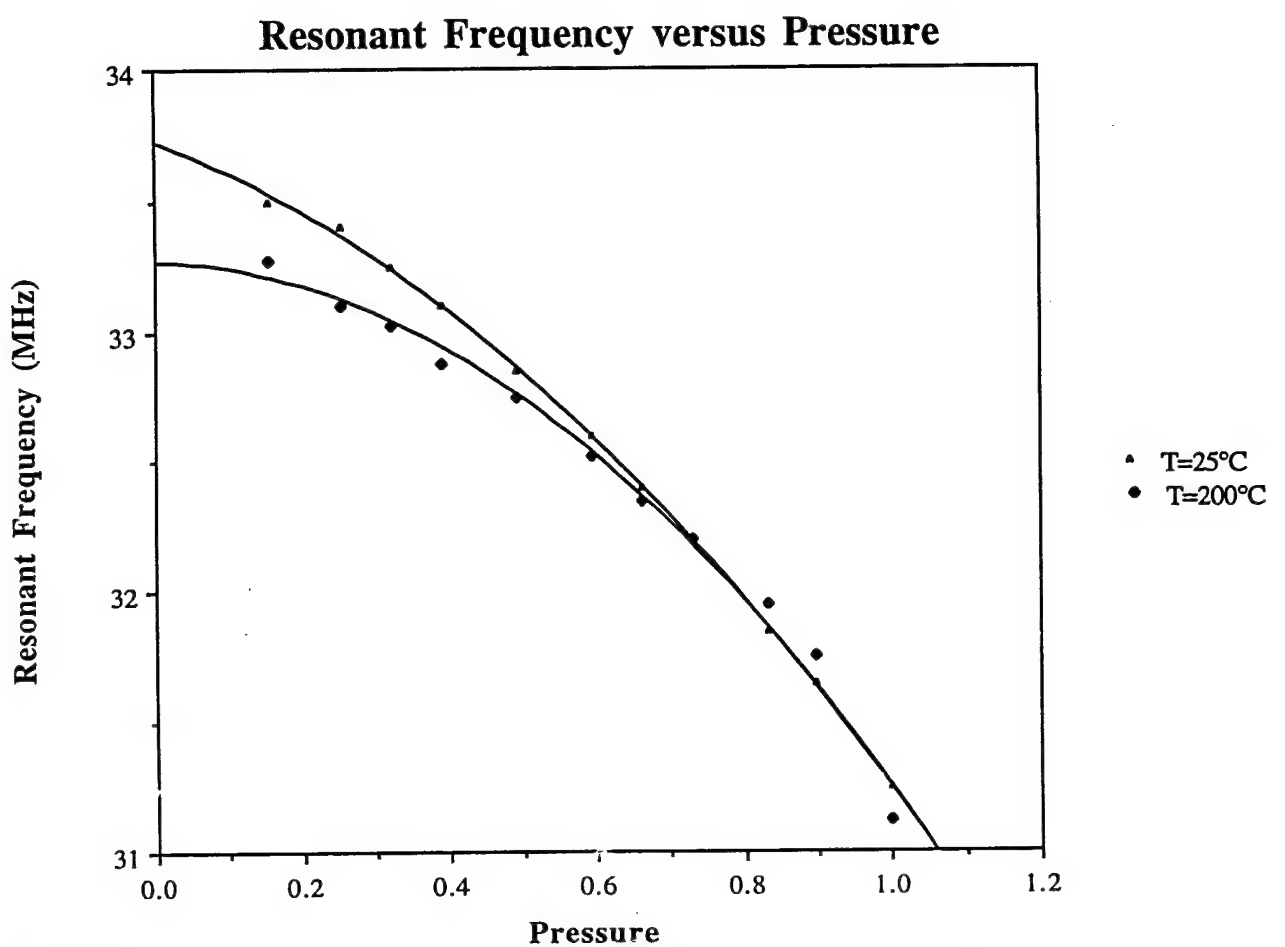
Resonant Frequency versus Pressure
Resonant Frequency (MHz)
34.00
33.75
33.50
33.25
33.00
32.75
32.50
32.25
32.00
31.75
31.50
31.25
31.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Pressure

Results

Phase versus Frequency for Array Interrogation



Results



Resonant Frequency versus Pressure
34
33
32
31
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Pressure
Resonant Frequency (MHz)
T=25°C
T=200°C

Future Work

- Operate integrated sensor at higher temperatures (200°C-600°C) and higher pressures (1-25 atm).
- Improve pressure sensitivity.
  - Vary sensor membrane diameter and geometries.
  - Vary thicknesses of ceramic tape.
  - Experiment with ceramic slurries.
- Improve temperature sensitivity.
  - Capacitor electrodes to the inside of sensor.
  - Build on-board temperature sensor for correction if necessary.
- Continue experiments with health monitoring devices.

Diode-laser sensors for active control of gas turbines

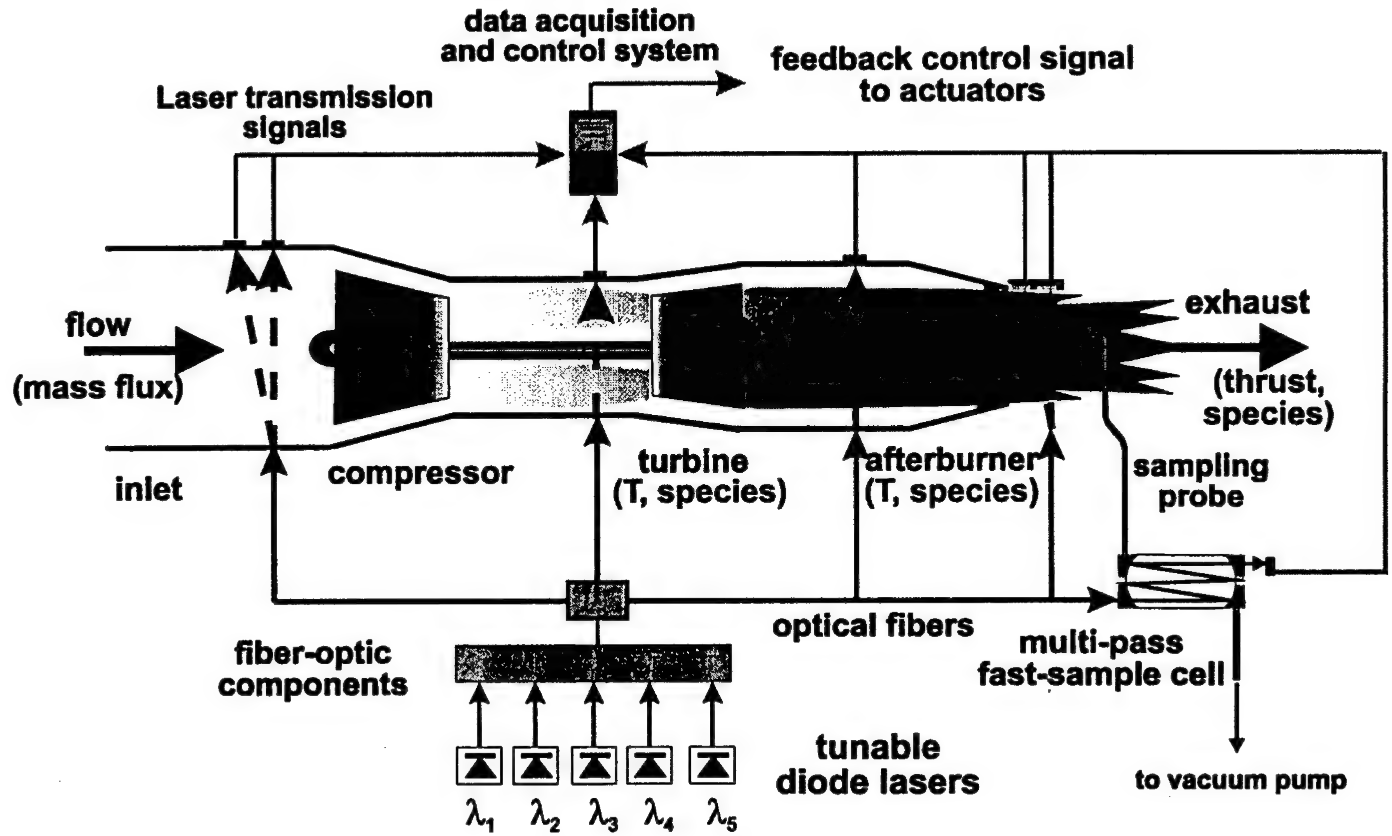
R.K. Hanson
High Temperature Gasdynamics Laboratory
Stanford University

- Diode laser history
- Theory of absorption spectroscopy
- H_2O and T measurements (λ = 1.3-1.4 μm)
- Demonstration of control strategies
- CO_2 measurements (λ = 2 μm)
- Future applications

Diode-laser sensor developments at Stanford

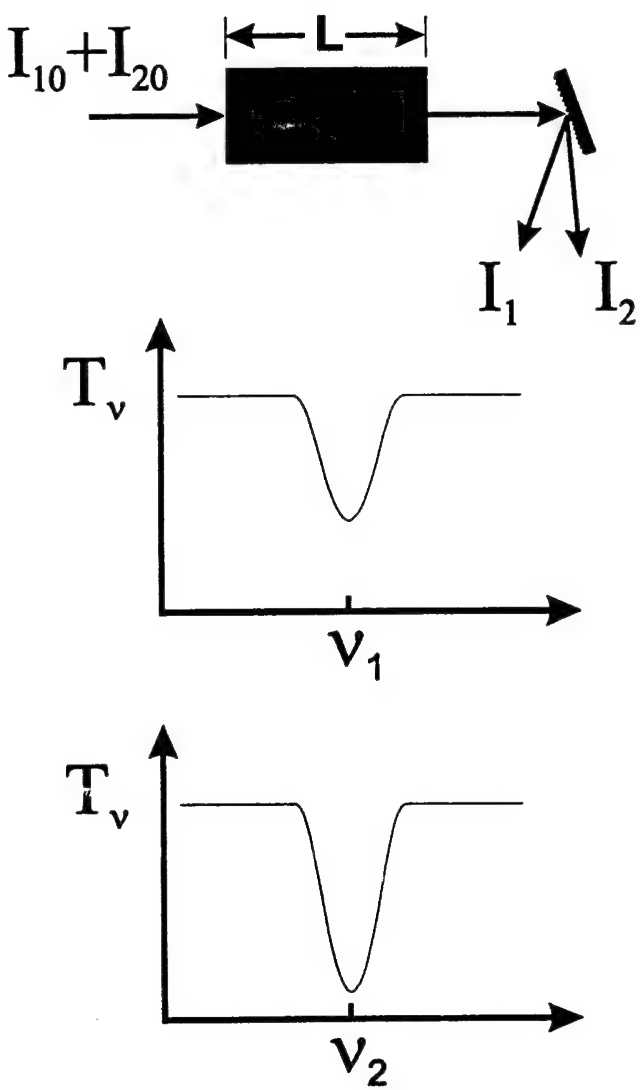
760 nm	• O_2 mass-flux sensor (1989)
777-845 nm	• Plasma (O, N, Xe; n_e, T) diagnostics (1990)
1.38 μm	• H_2O mass- and momentum-flux sensor (1992)
1.34, 1.39 μm	• Multiplexed sensors for T, H_2O measurements (1993)
395 nm	• NO_2 measurements near 395 nm and 670 nm (1995)
1.40 μm	• High-pressure H_2O measurements (1996)
1.39, 1.40 μm	• Hypervelocity flowfield measurements (1996)
1.55-1.80 μm	• Fast-sampling techniques for combustion emissions measurements of CO, CO_2, NO, NO_2, UHC (1996)
1.34, 1.39 μm	• Combustion control (1996)
2.0 μm	• *In situ* CO_2 measurements (1998)
2.3, 2.7 μm	• Sensitive CO, NO, H_2O measurements (1999 ?)

Our vision: Multiplexed diode-laser sensors for gas turbine sensing and control



- Real-time measurements of T, combustion products, mass flux, and thrust
- Fiber-optic system is compact, flexible, and rugged
- Fast extractive sampling technique allows sensitive emissions monitoring
- Multiplexing allows simultaneous multi-species monitoring at multiple locations

Theory of absorption measurements



- **Beer – Lambert relation**

$$T_\nu \equiv \frac{I_\nu}{I_0} = \exp(-k_\nu L)$$

- **Spectra absorption coefficient**

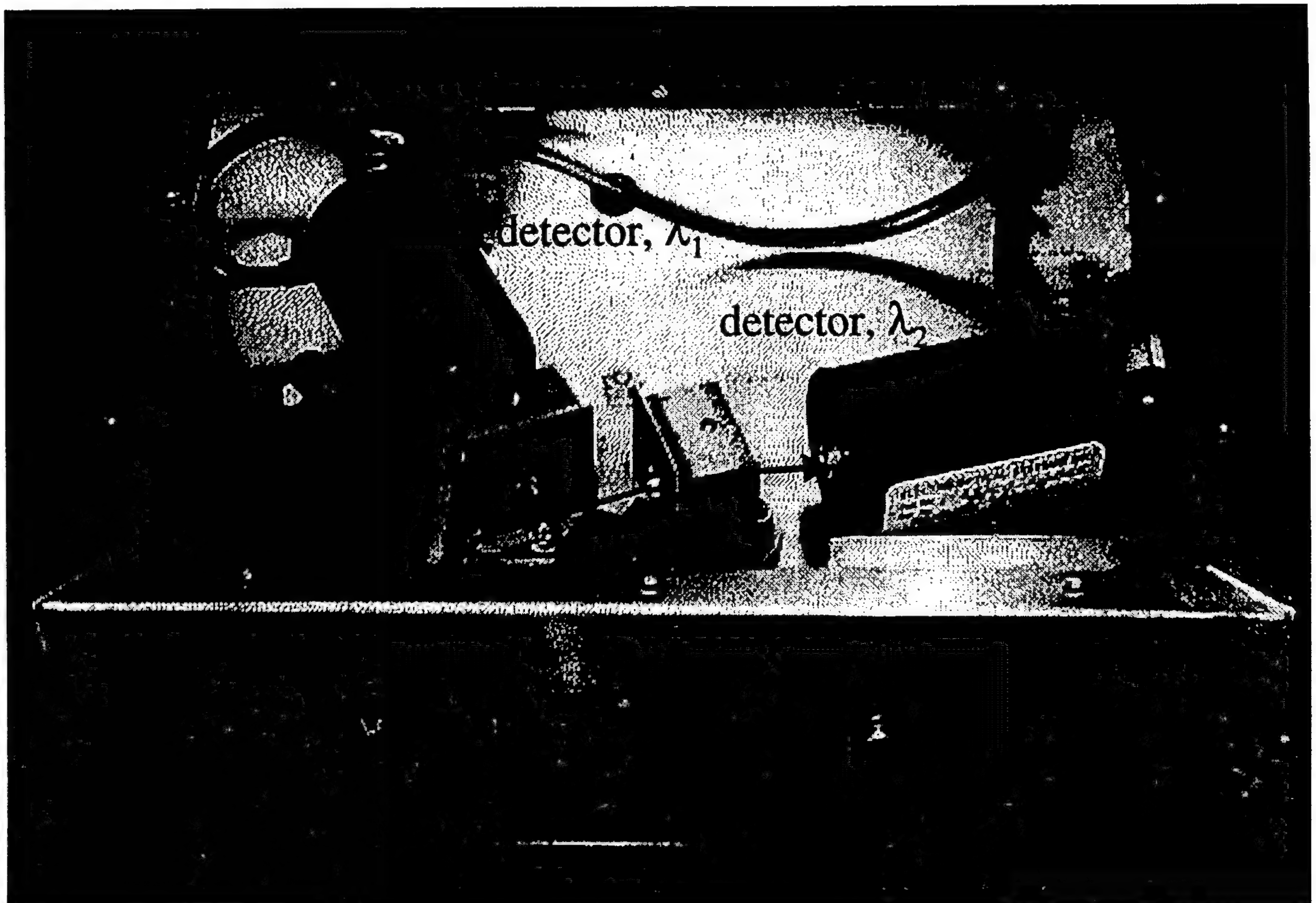
$$k_\nu = S(T)\,P\,X\,\phi(\nu)$$

- **Ratio yields T**

$$\frac{k_1}{k_2} = \frac{S_1(T)\,\phi_1(\nu)}{S_2(T)\,\phi_2(\nu)} \approx f(T)$$

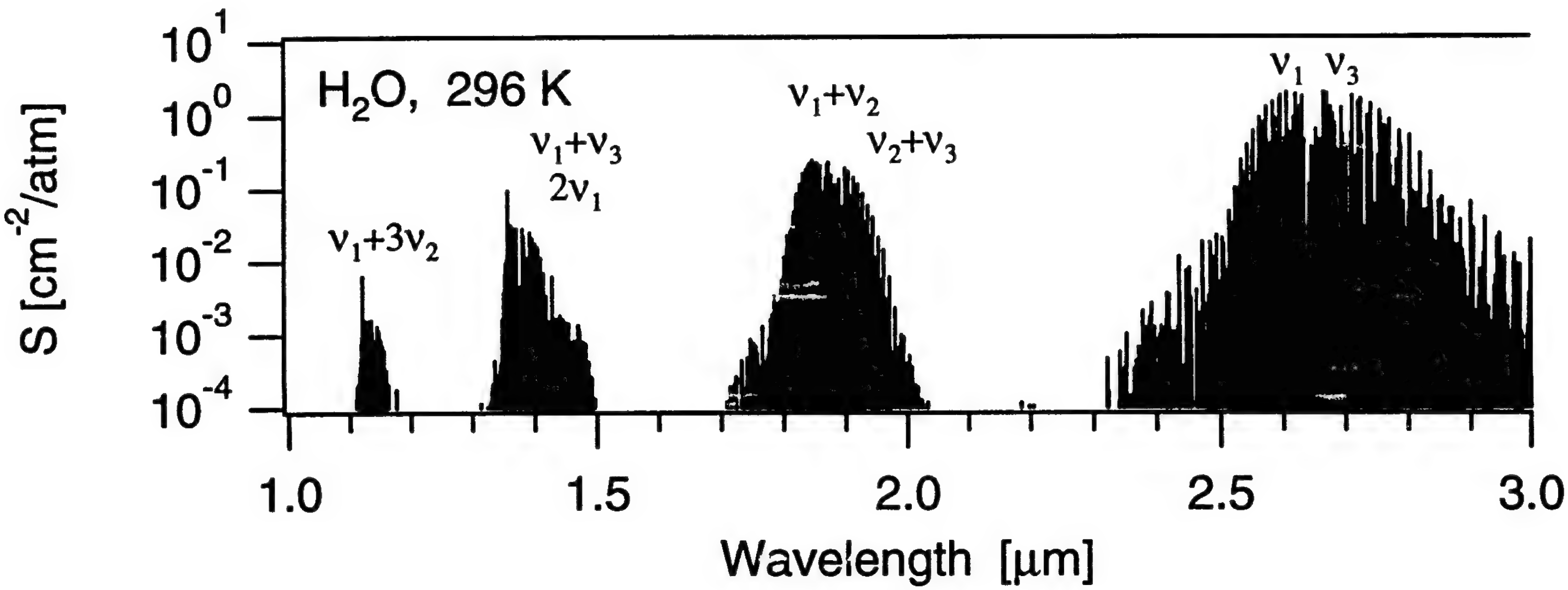
- **T and k_ν yield X**

Wavelength Demultiplexing Strategy



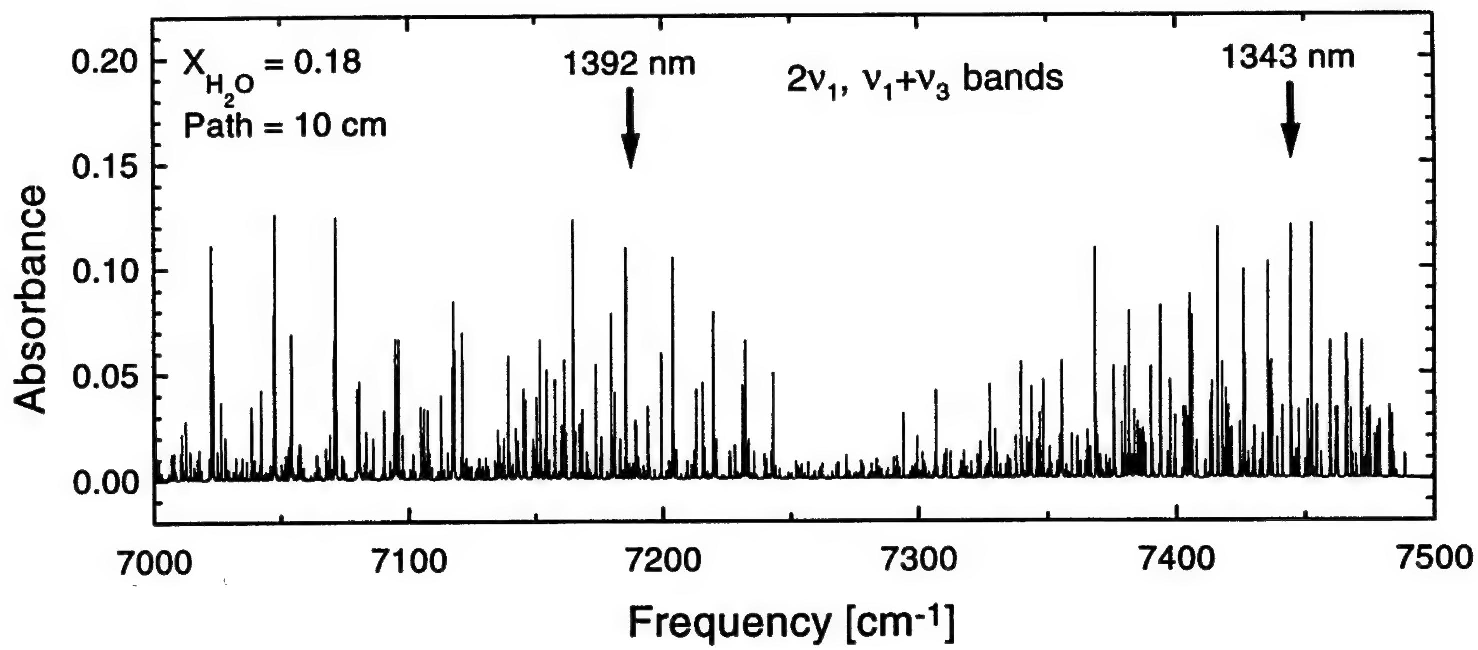
H_2O is attractive for combustion control

Multiple strong absorption bands



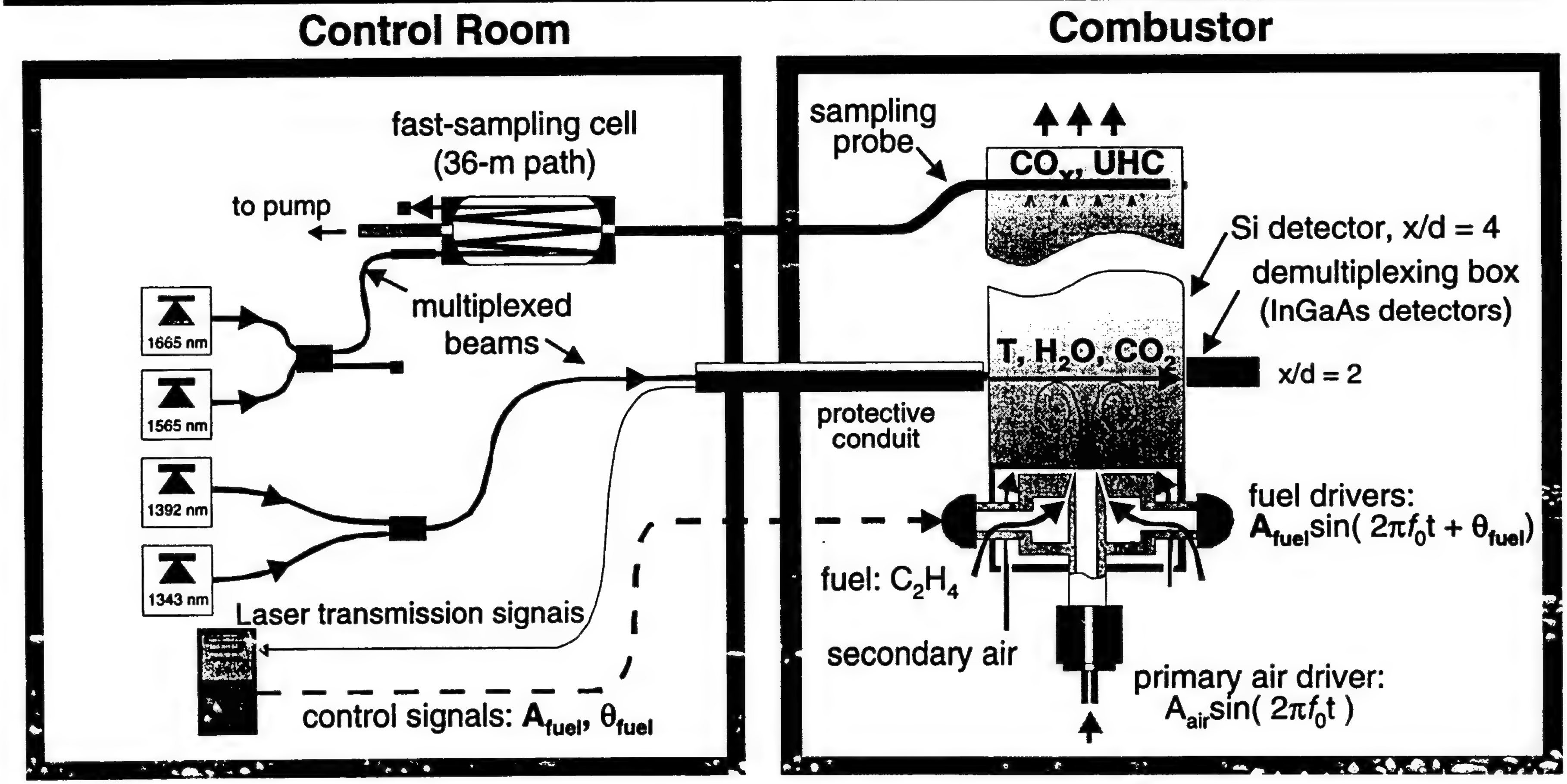
- H_2O is a major product species
- Diode lasers commercially available: 0.6 - 2.0 μm
- Transitions near 1.34 μm, 1.39 μm selected for temperature sensitivity

Calculated H_2O absorption spectrum (at 2000 K)



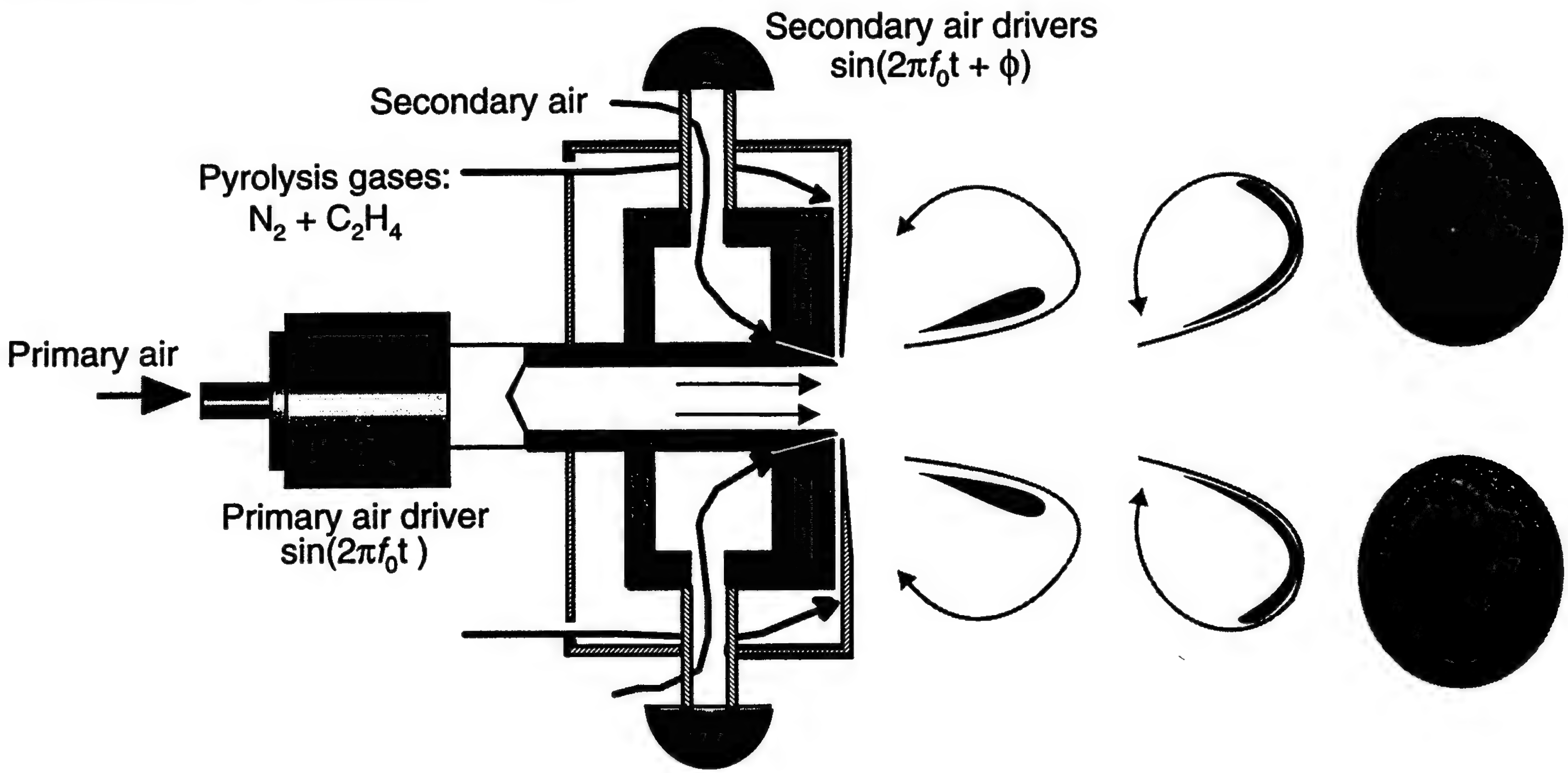
- **Spectrum more complex at high temperatures**
- **Transitions selected to maximize temperature sensitivity**

TDL concepts evaluated in a forced-vortex combustor



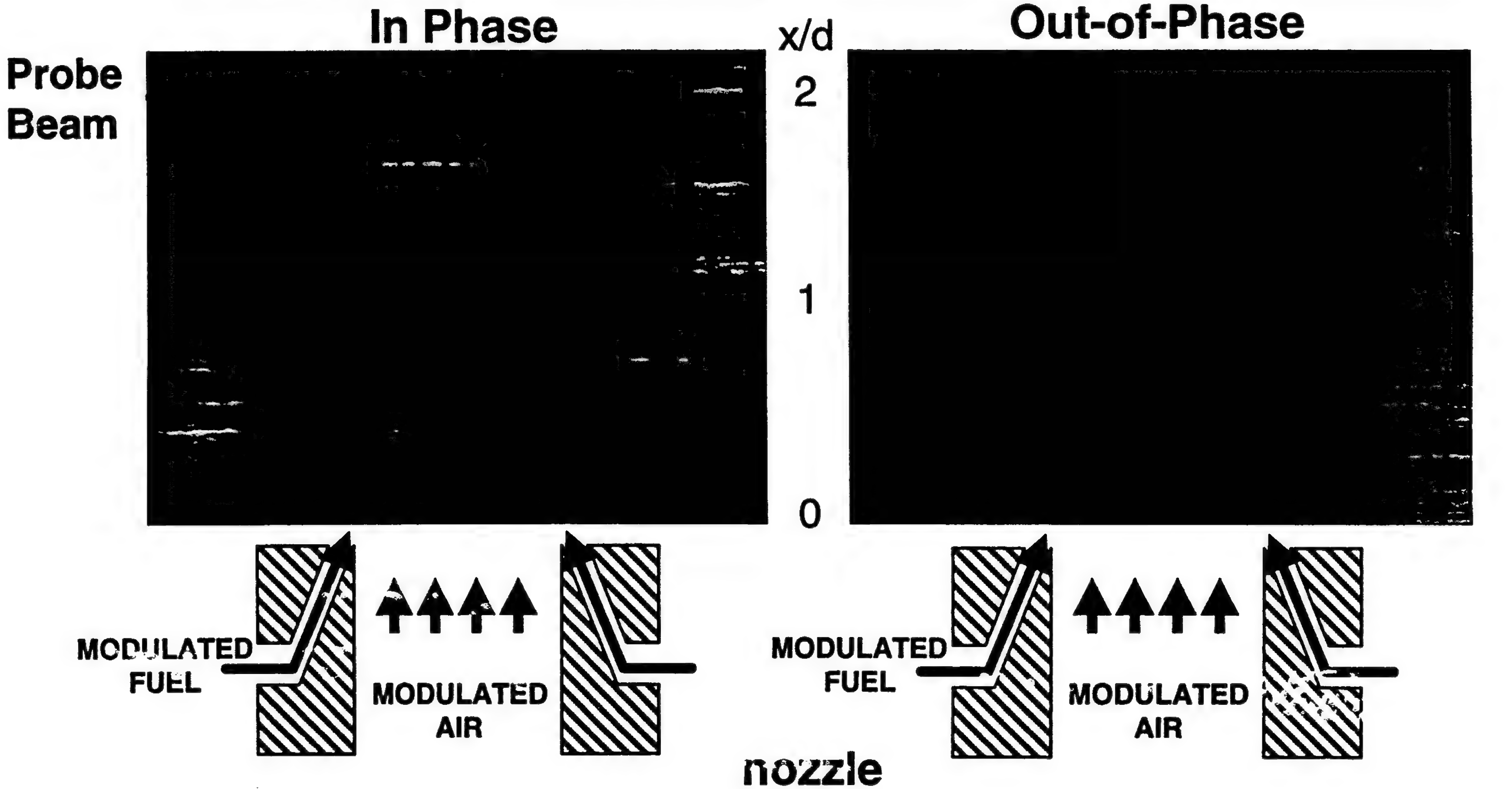
- T, X_{H2O} determined from laser transmission signals (near 1.34 μm, 1.39 μm)
- Magnitude of oscillations at forcing frequency, $T_{rms}(f_0)$, calculated from T(t)
- Control system varies phase θ_{fuel} between fuel, air drivers to maximize $T_{rms}(f_0)$

Forced Vortex Concept for Enhanced Mixing



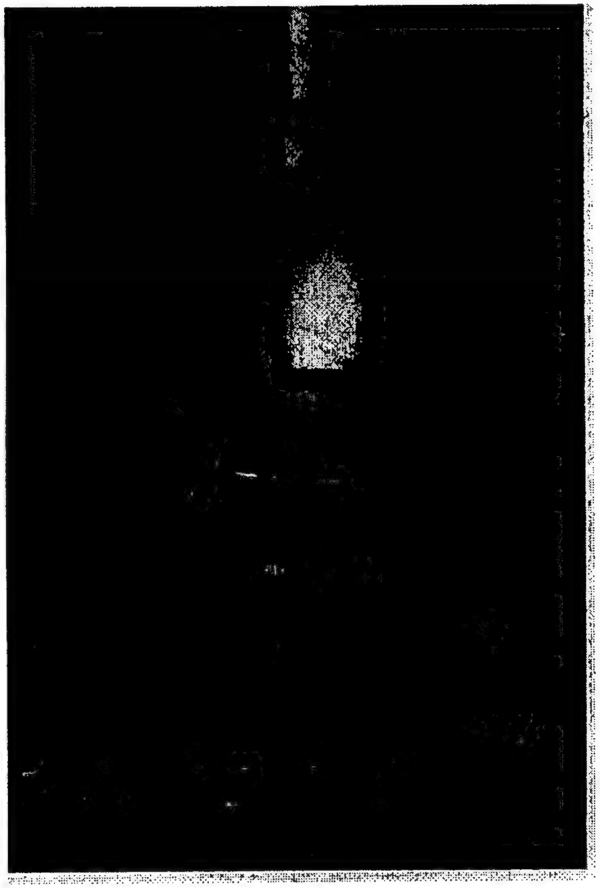
- Acoustic forcing generates coherent vortices
- Fuel injection at proper phase yields improved fuel-air mixing
- Subsequent heat release is periodic and results in T oscillations

Acetone, OH PLIF Images (5-kW combustor, Parr et al)

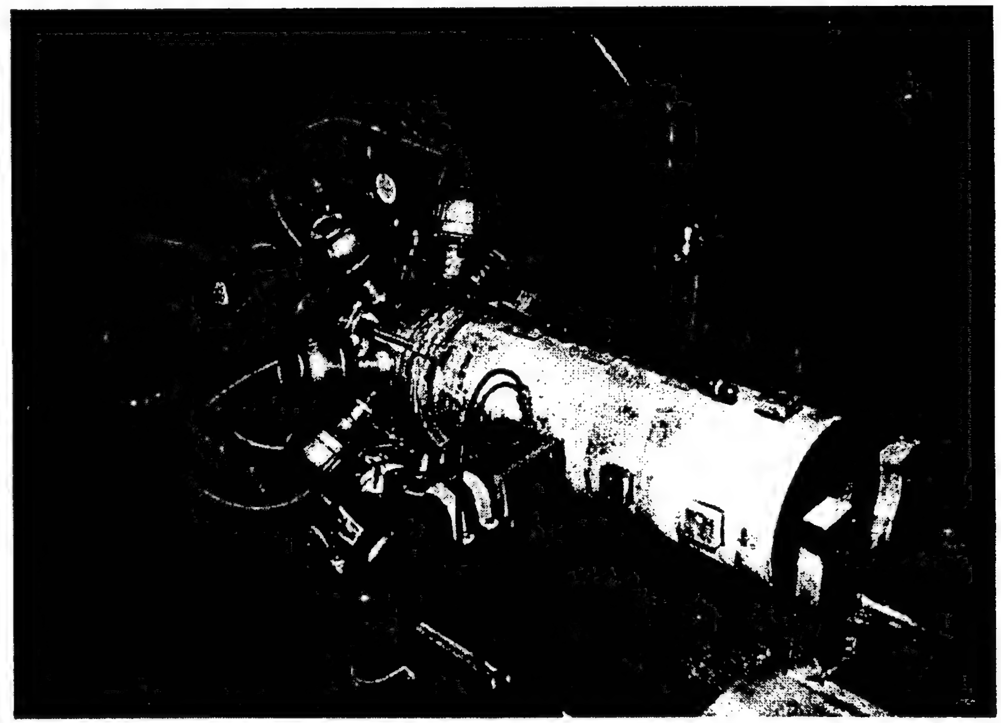


- In-phase modulation improves fuel-air mixing and leads to reduction in CO, NO_x, UHC emissions

Sensor system applied to small- and large-scale facilities

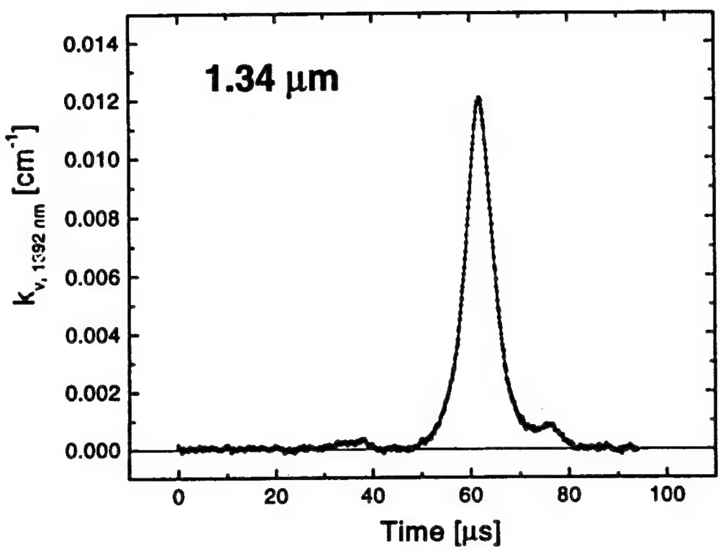


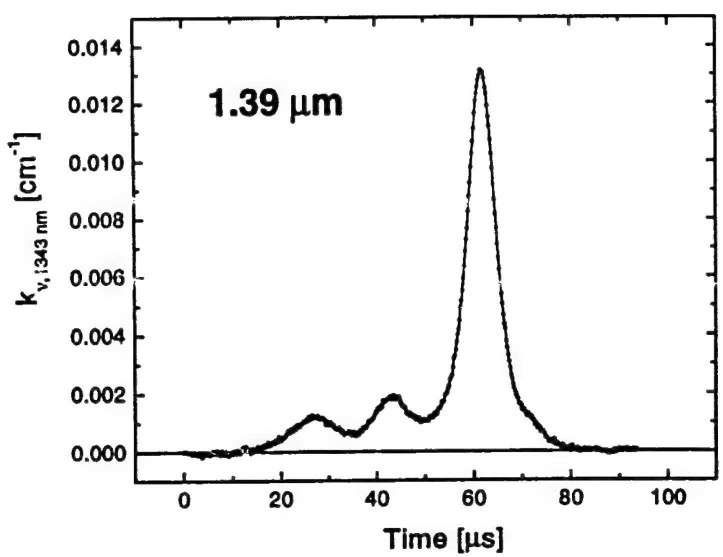
5-kW Forced Combustor
HTGL, Stanford University



50-kW Forced Combustor
NAWC, China Lake, CA

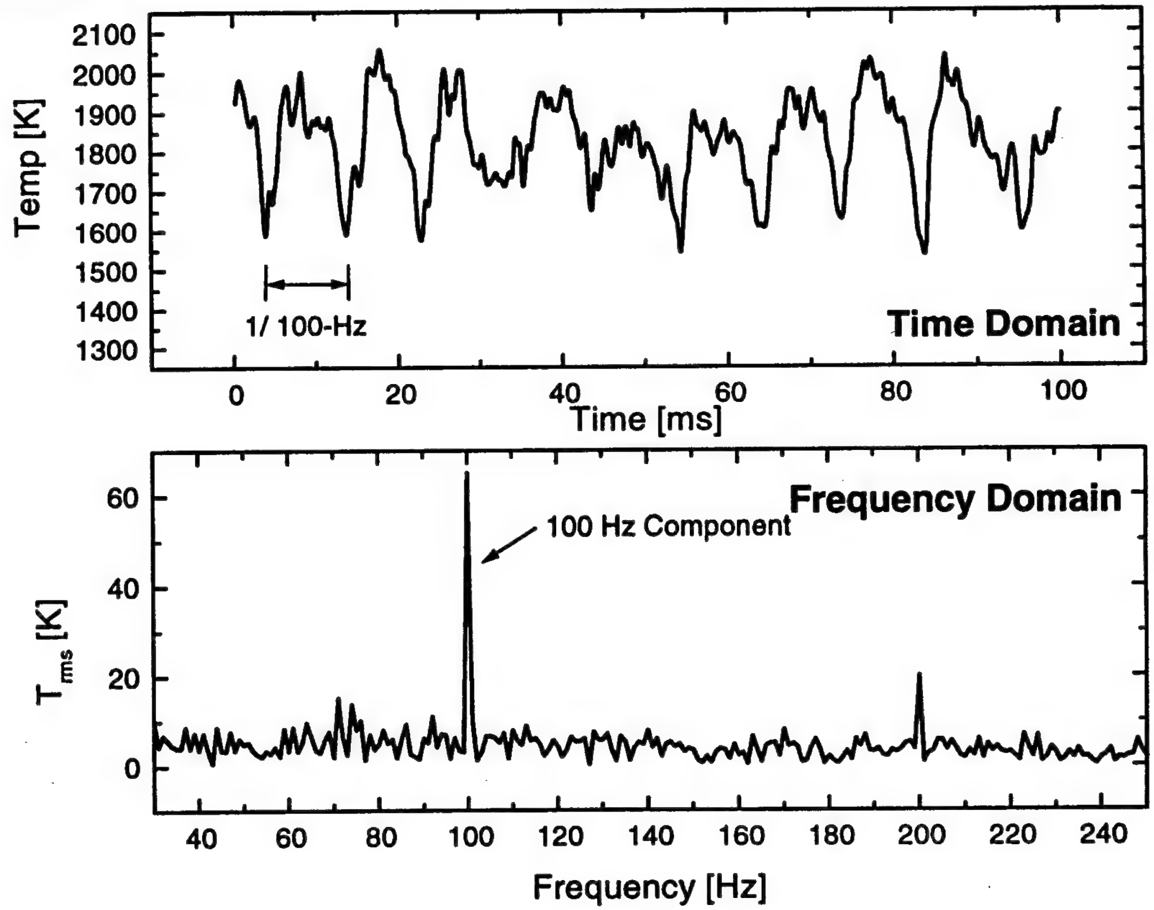
Single-sweep data traces: Laser transmission through post-flame gases





- $k_\nu = -\ln(T_\nu)$
- Ratio of k_ν peaks yields T
- Peaks measured simultaneously
- SNR ~ 200
- Absolute accuracy of T as set by spectroscopic parameters ~ 6 %

Time-resolved T measurements in SU combustor

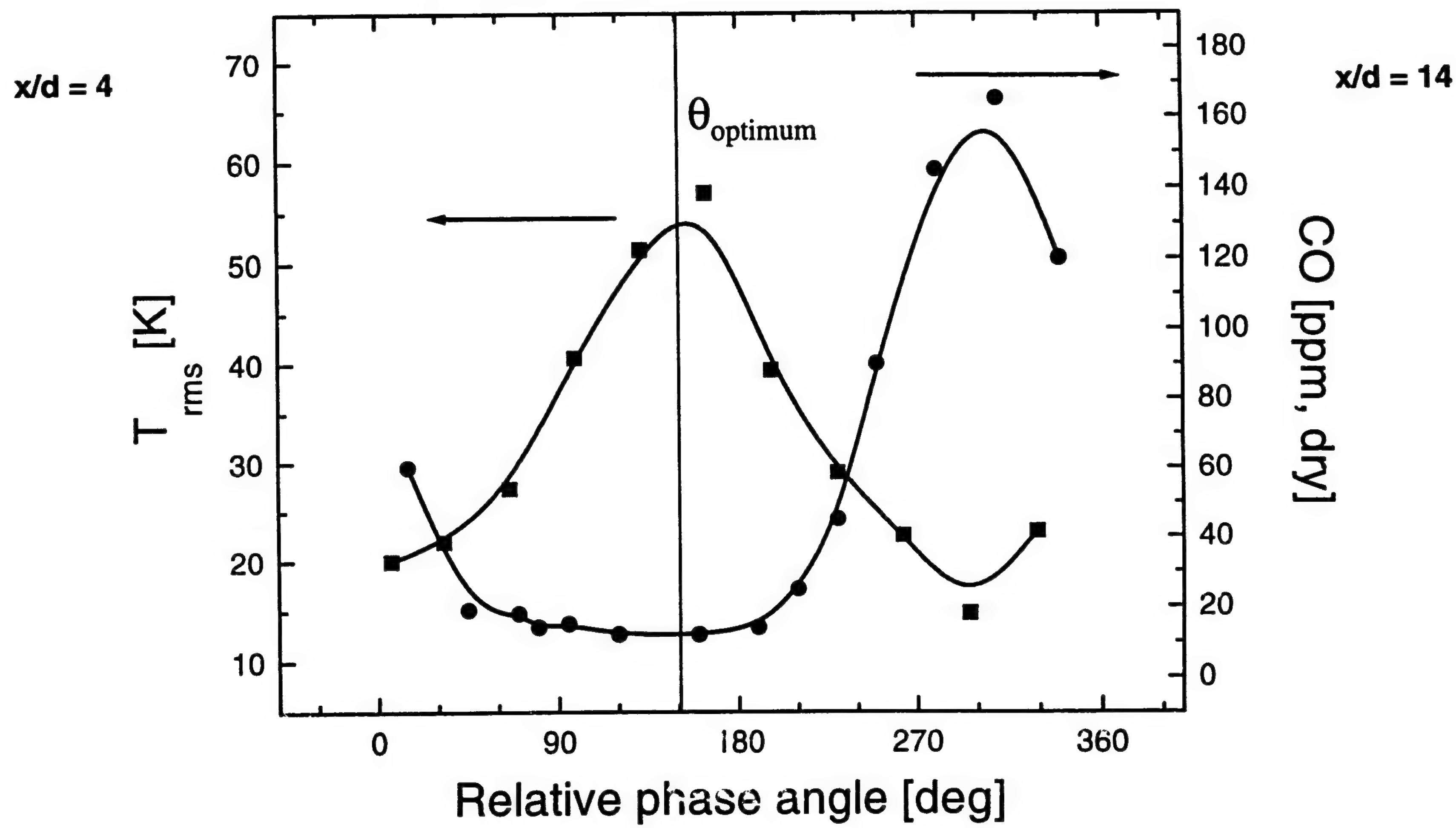


Operational Parameters

x/d = 2
ϕ = 0.75
f_0 = 100 Hz

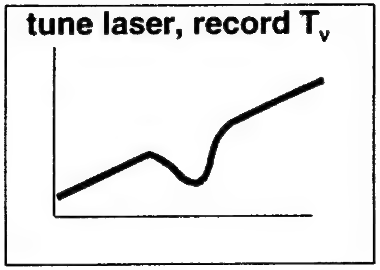
- **Fast measurements (10 kHz) enables real-time control strategies**
- **Fourier analysis of T(t) yields $T_{rms}(f_o)$, a measure of combustor performance**

Measured correlation between T_{rms} and CO (50-kW combustor at China Lake)

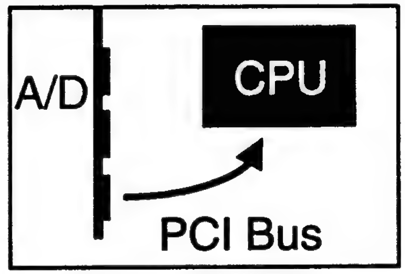


- CO concentration near minimum when T_{rms} near maximum

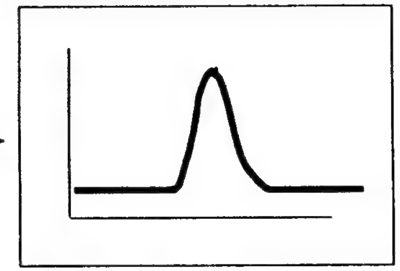
Closed-loop control procedure



step 1: 100 μs
acquire absorption spectra



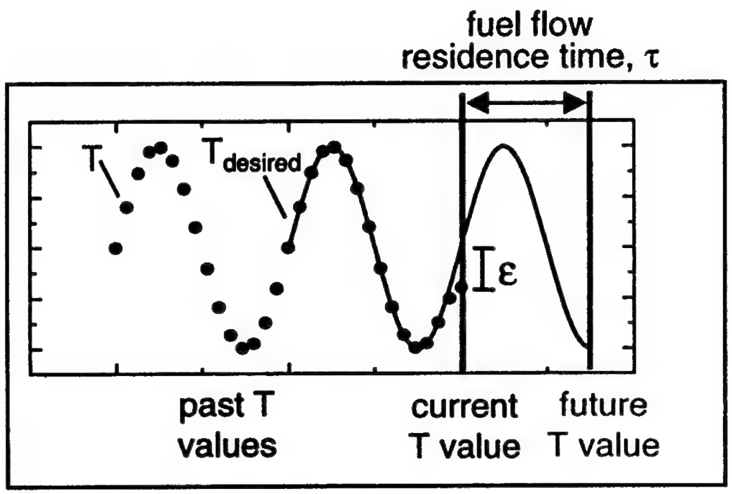
step 2: 200 μs
transfer data



step 3: 70 μs
(in parallel with acquisition)
analyze data,
determine T, P_{H_2O}

step 4: 10 μs
(in parallel with acquisition)
evaluate error,
$\varepsilon = T - T_{desired}$

Compute A_{fuel}, θ
for fuel actuators



step 5: 1.0 μs
send feedback
signal to actuator

- **New control decision (A_{fuel}, θ) every 300 μs**

15

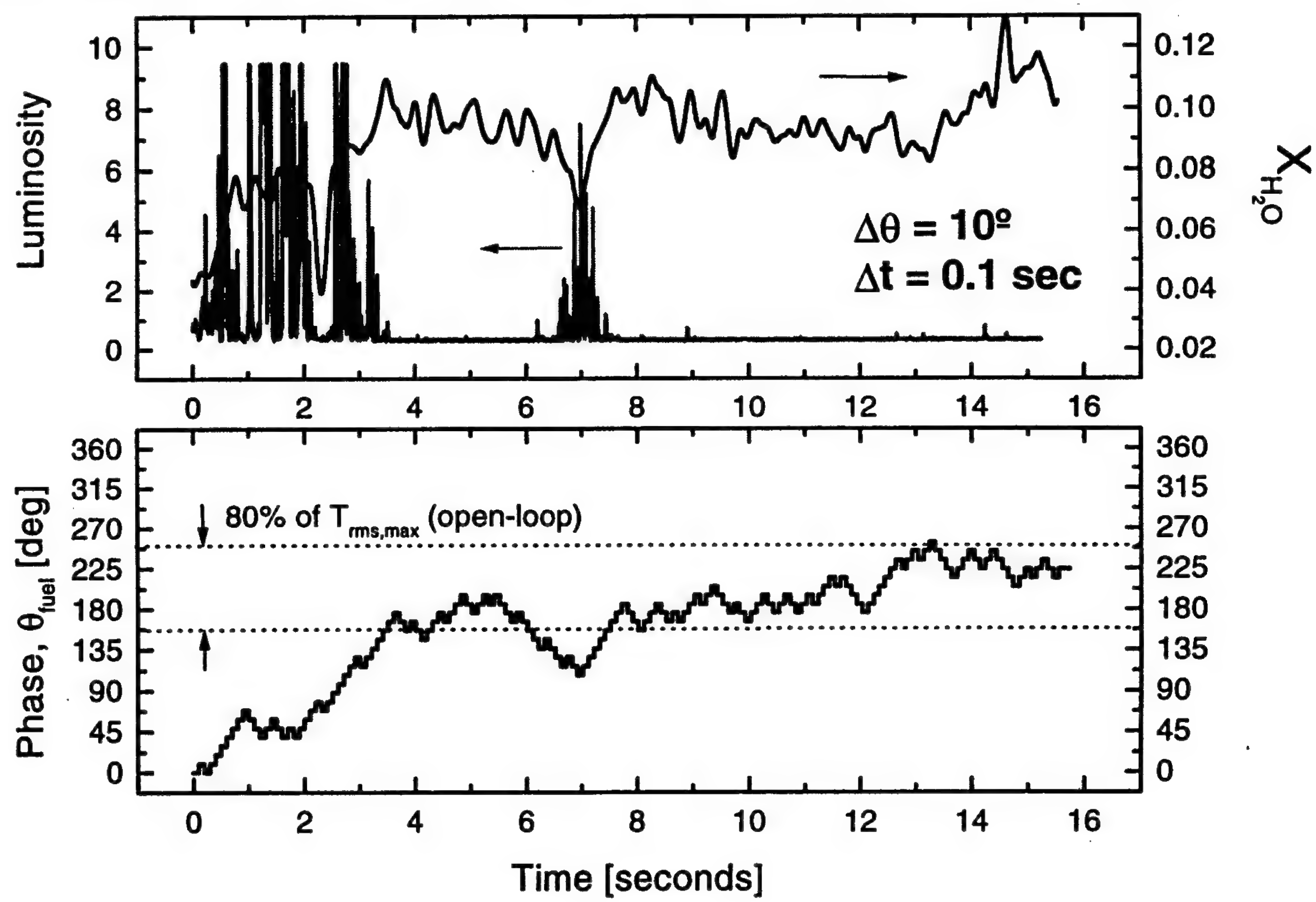
3 control strategies applied to SU combustor

Strategy 1: Hill-Climbing algorithm varies θ_{fuel}

Goal: maximize extent of reaction (X_{H2O}) at measurement location

1. Adjust θ_{fuel} by $\Delta\theta$ degrees (fixed step); A_{fuel} = constant
2. Measure X_{H2O} for Δt seconds to determine flowfield response
3. If performance improves (X_{H2O} increases), repeat adjustment
4. If performance degrades (X_{H2O} decreases), reverse adjustment
5. $\Delta\theta$, Δt steps determine convergence speed, amplitude of limit cycle

Closed-Loop Control: Strategy 1



- Hill-Climbing strategy maximizes X_{H2O} by adjusting θ_{fuel}
- convergence time ~ 10 seconds

Strategy 2: LMS algorithm varies A_{fuel} and θ_{fuel}

Goal: optimize coherence of T oscillations (maximize T_{rms})

1. **Decompose measured T(t) into three components**

   $$T(t) \sim T_{mean} + T_{rms} \sin(2\pi f_0 t - \theta_1) + \text{harmonics}$$

2. **Extract T_{rms}, θ_1**

3. **Evaluate error function**

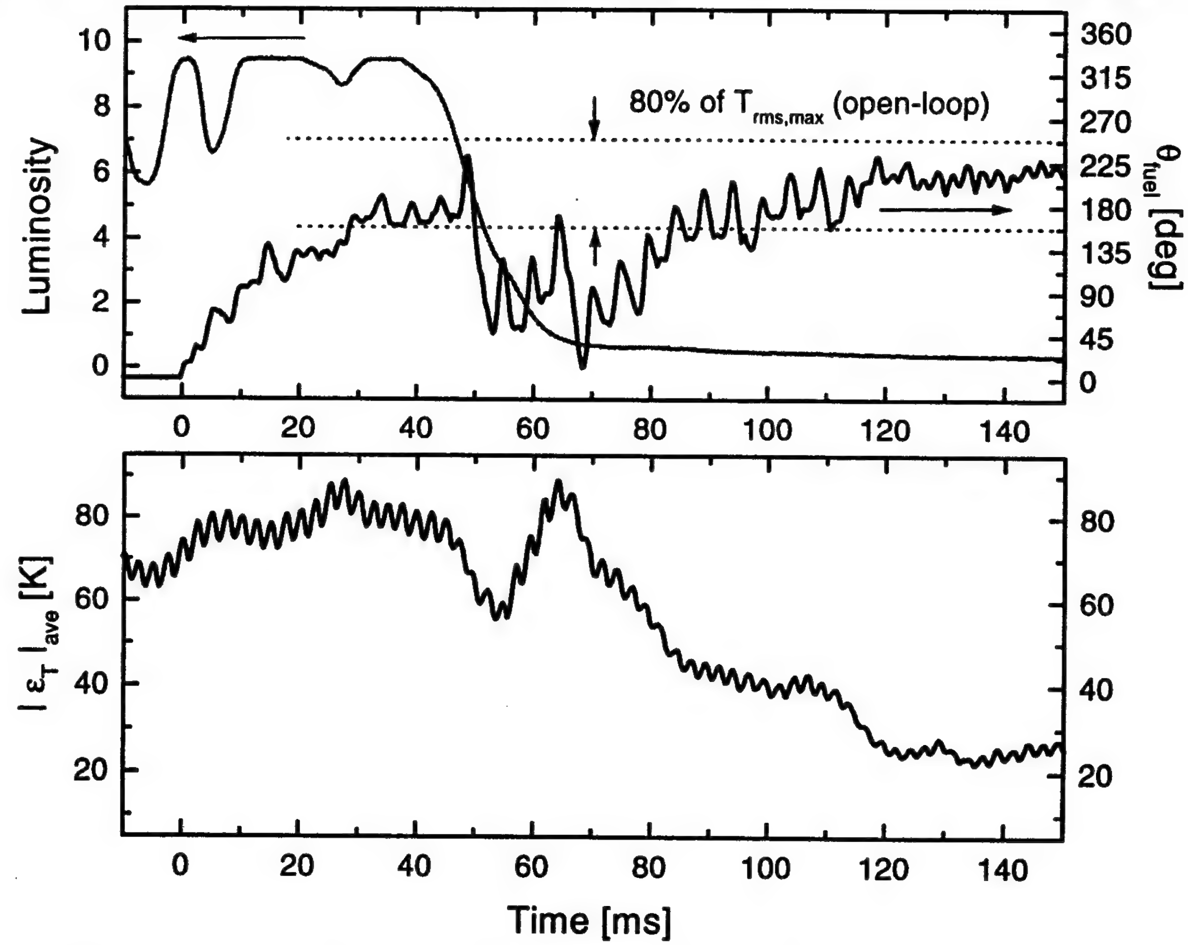
   $$\varepsilon_T \equiv T_{desired} - T_{measured} = T_{rms,des} \sin(2\pi f_0 (t - \tau_{act})) - T_{rms} \sin(2\pi f_0 t - \theta_1)$$

4. **Minimize error ε_T by adjusting A_{fuel} and θ_{fuel} (for time constant τ_{adapt})**

   $$\theta_{fuel,new} = \theta_{fuel,old} - (C/\tau_{adapt})\, \varepsilon_T A_{fuel,old} \cos(2\pi f_0 t + \theta_{fuel,old})$$

   $$A_{fuel,new} = A_{fuel,old} + (C/\tau_{adapt})\, \varepsilon_T \sin(2\pi f_0 t + \theta_{fuel,old})$$

Closed-Loop Control: Strategy 2



Operational Parameters

x/d = 2
$\phi = 0.75$
$f_0 = 100$ Hz

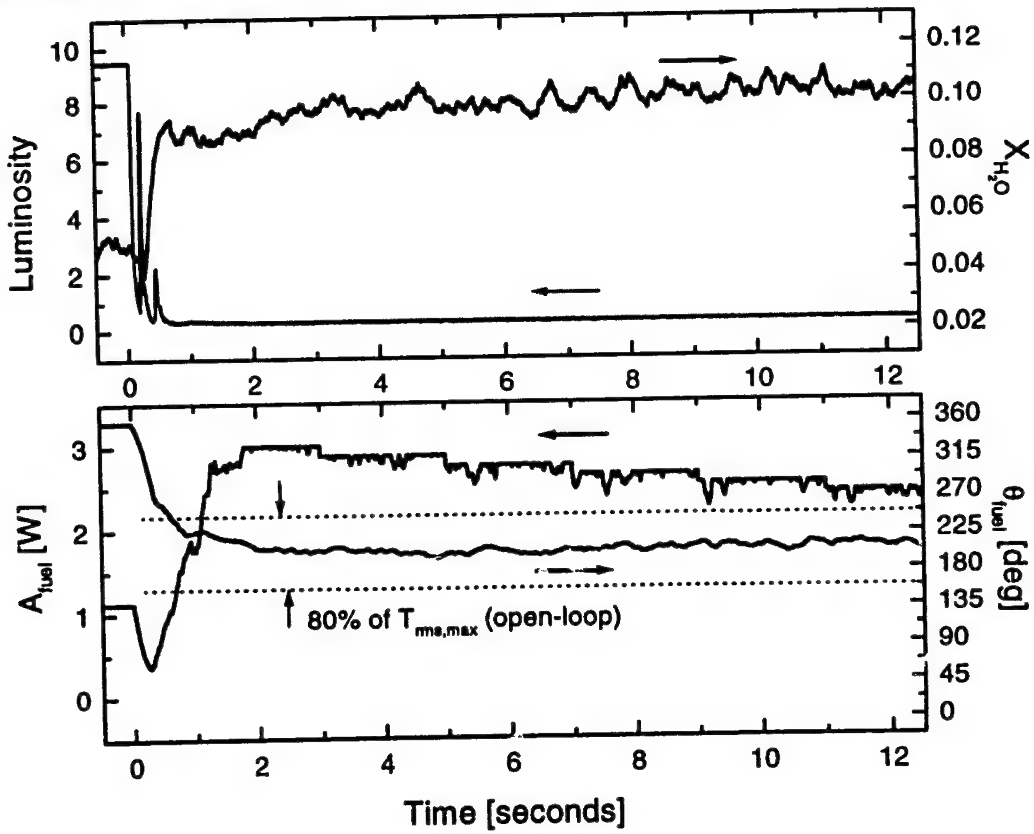
$\tau_{adapt} = 42$ ms

- **Performance optimized within 120 ms (100x improvement over Strategy 1)**
- **Corresponds to only 7 flowfield residence times ($\tau_{flow} = 14$ ms)**
- **τ_{adapt} determined via open-loop experiments**

Strategy 3 (combines merits of 1 and 2)

Goal: optimize vortex coherence (T_{rms}) *and* extent of reaction (X_{H2O})

- LMS algorithm adjusts θ_{fuel} to maximize T_{rms}
- Hill-Climbing algorithm adjusts A_{fuel} to maximize X_{H2O}



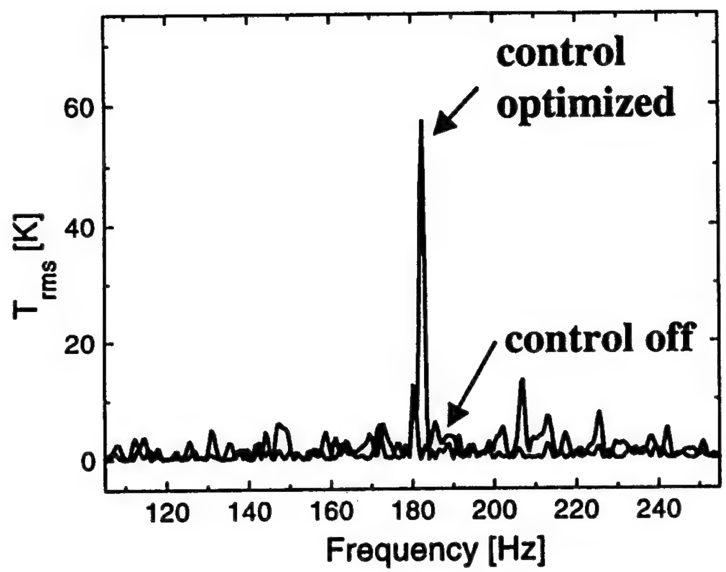
Operational Parameters

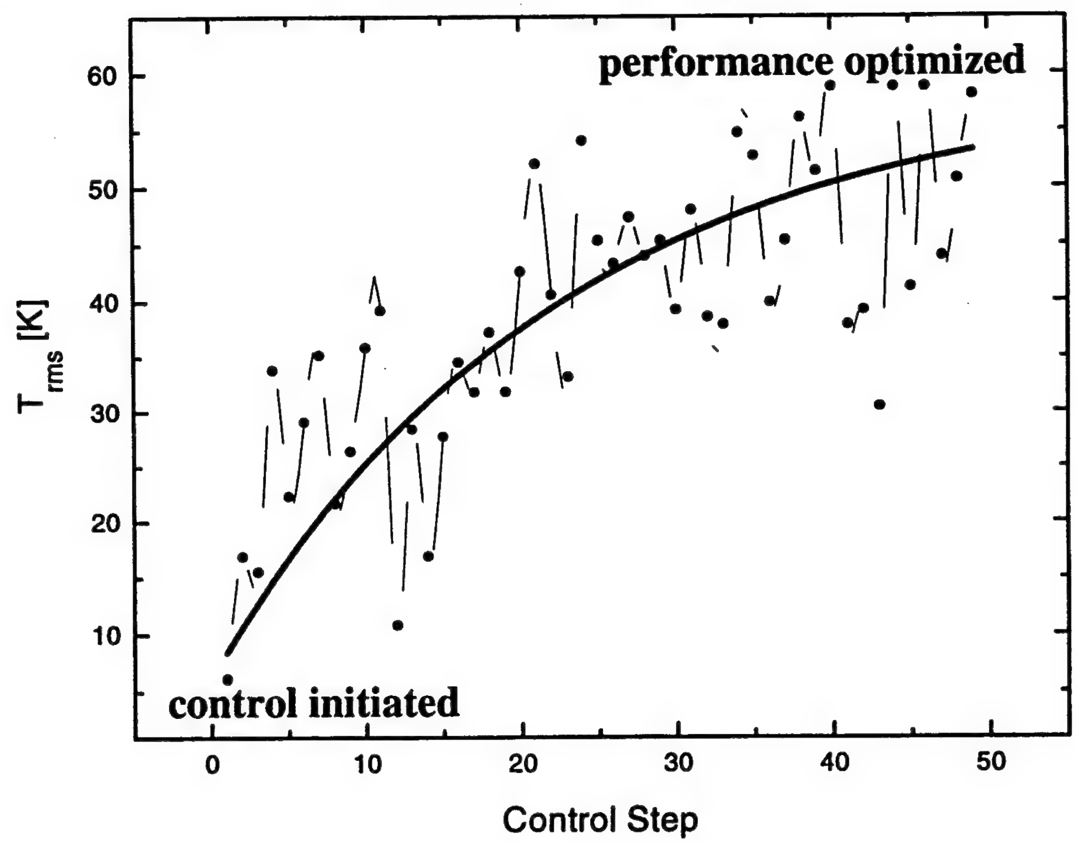
x/d = 2
$\phi = 0.75$
$f_0 = 100$ Hz

- **Response time for closed-loop control ≈ 1 second**

Demonstration of closed-loop control at China Lake

- Hill-climbing algorithm applied to maximize T_{rms}

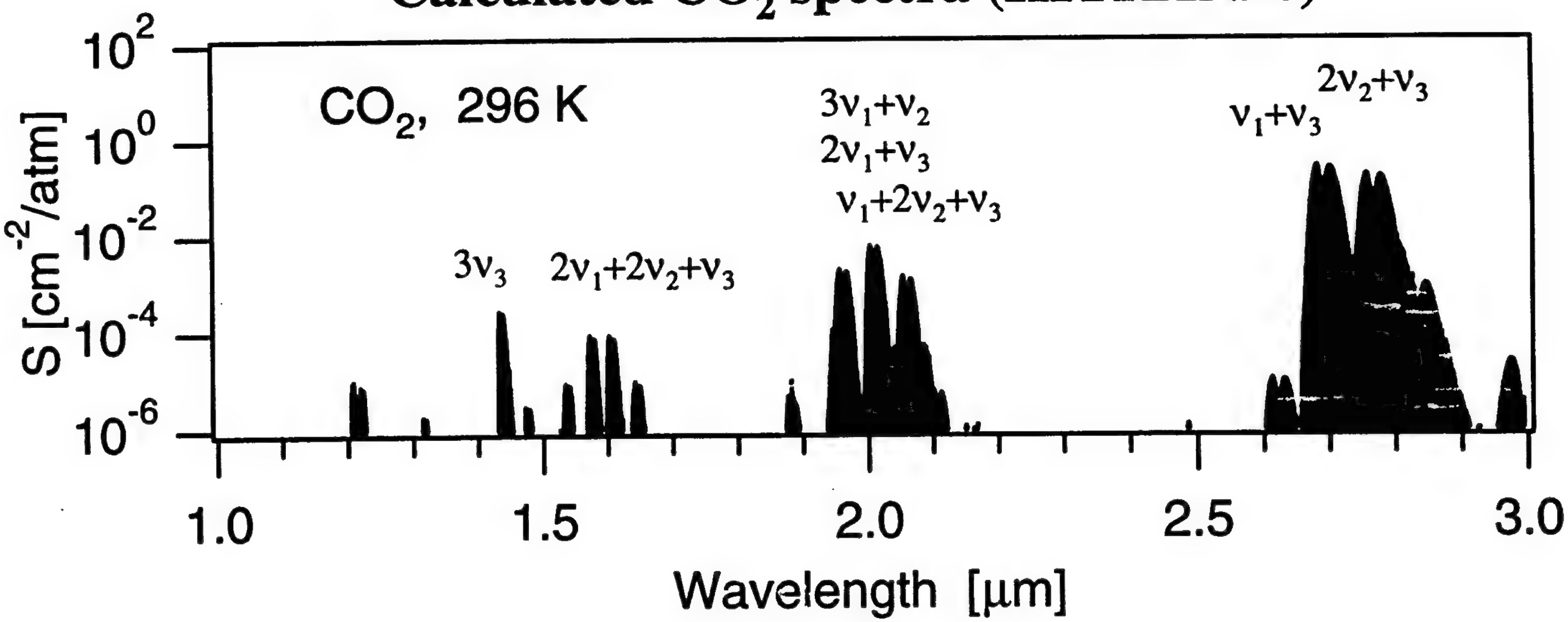




- Maximum T_{rms} yields optimum performance (minimum CO, UHC, C_6H_6 output)
- Future work will utilize improved strategies for faster response

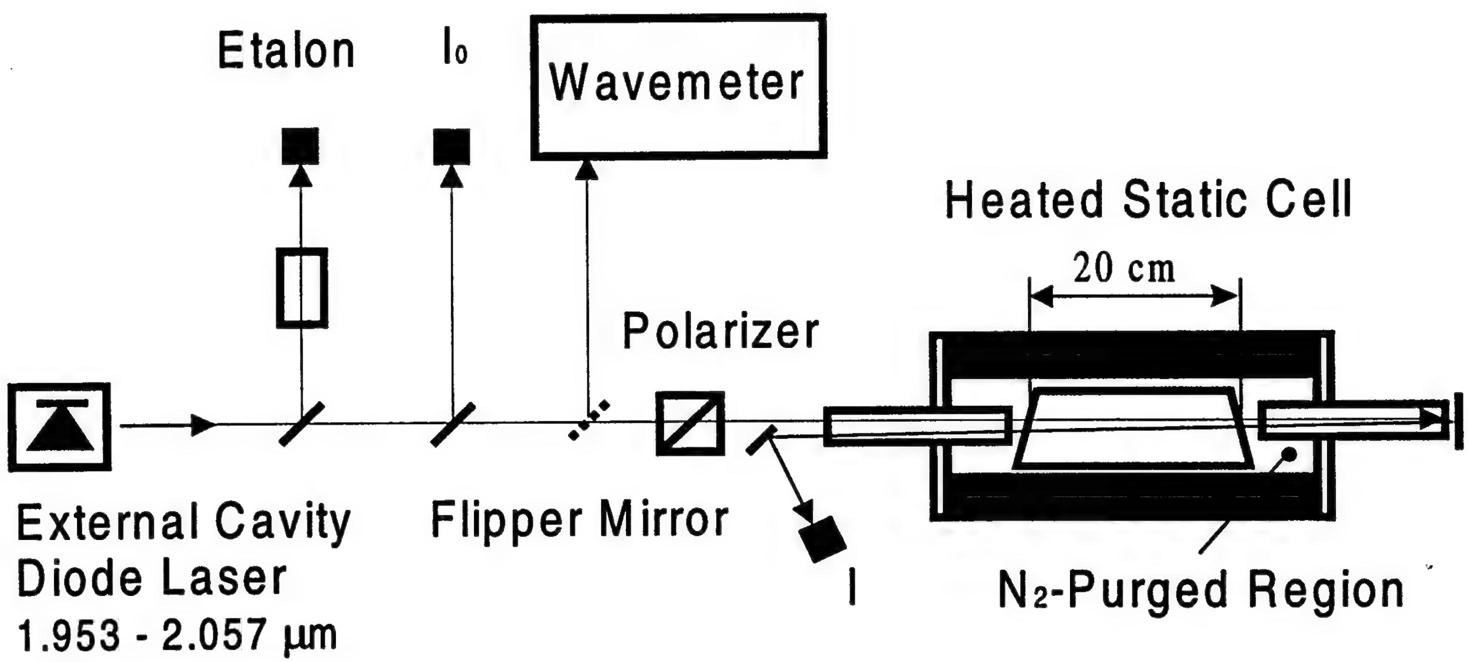
In situ CO_2 measurements enabled by 2.0-μm lasers

Calculated CO_2 spectra (HITRAN96)



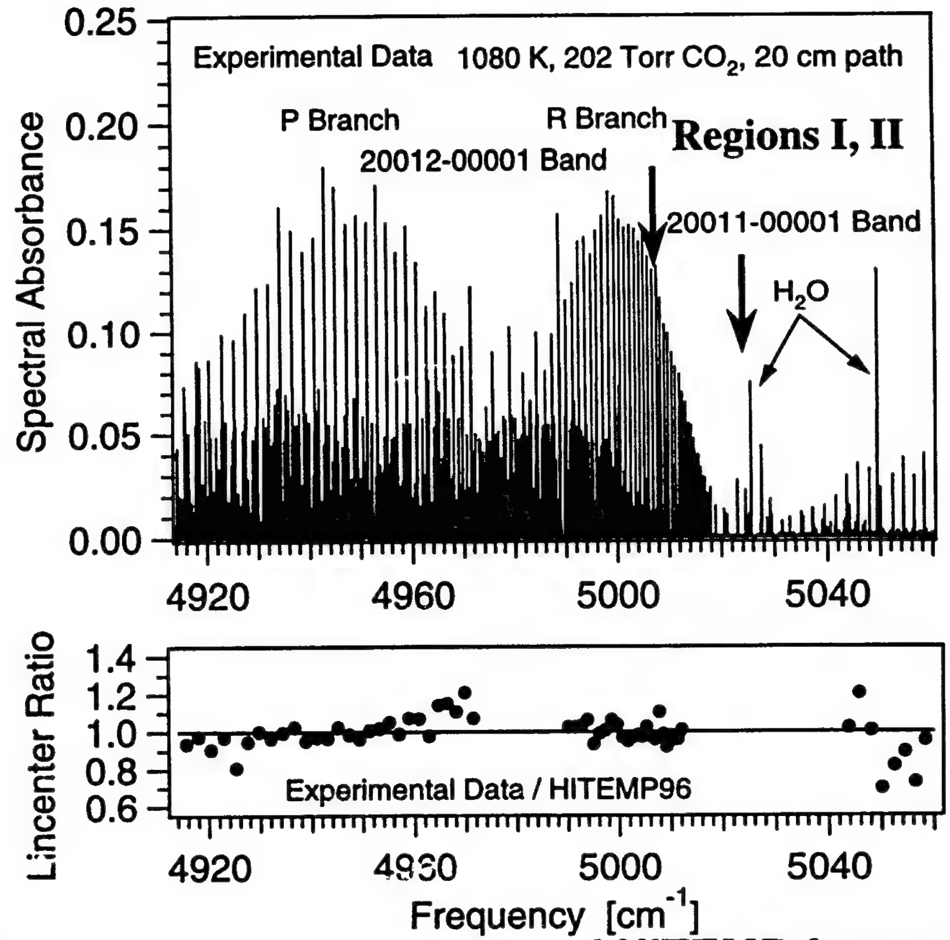
- First access to 2.0-μm external cavity diode laser
- Stronger line strengths promise increased measurement sensitivity
- Measurements reveal errors in HITEMP/HITRAN96 spectroscopic database

High-temp experiment to validate HITEMP database



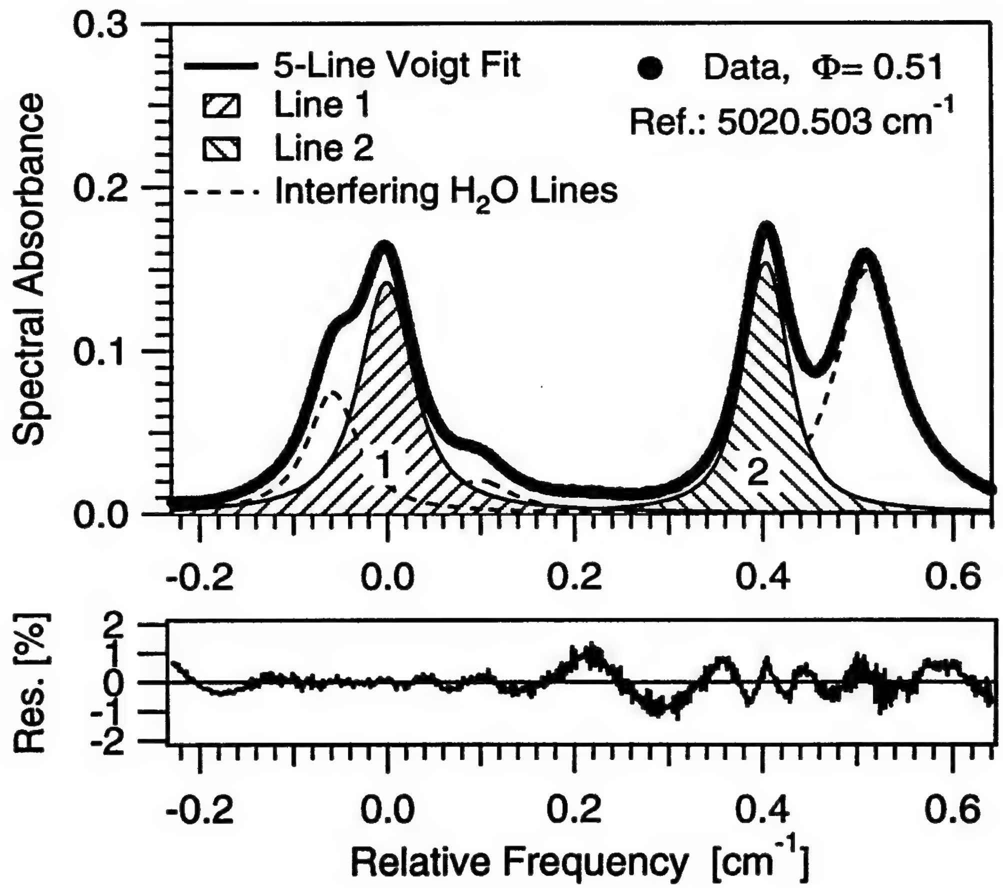
- **Temperature range in cell: 296 -1500 K**
- **Purge tubes reduce absorption due to cooler room air**

Comparison of measured and calculated high-temperature CO_2 survey spectra



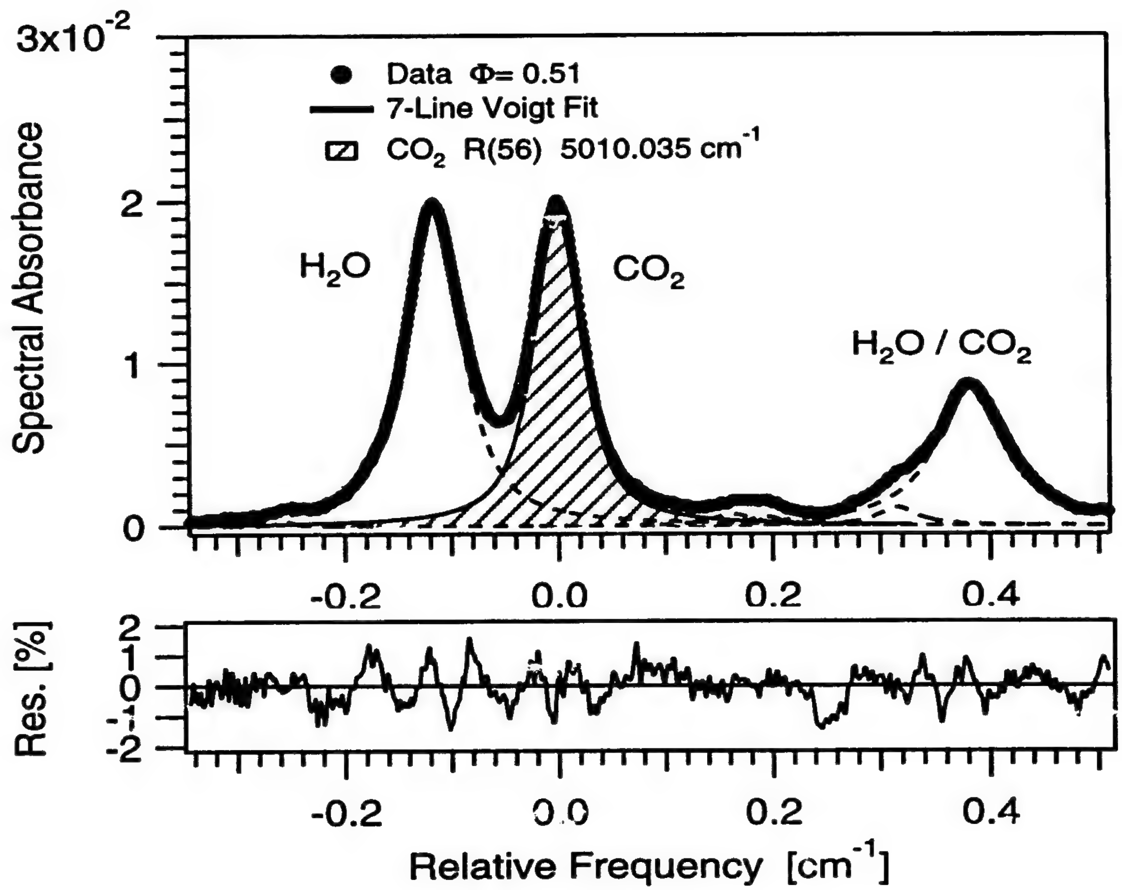
- Large variations between measurements and HITEMP for $\nu > 5020\ cm^{-1}$
- Transitions in Regions I, II selected for determination of T, CO_2, H_2O
- Region II (H_2O lines only); Region I (H_2O and CO_2 lines)

High-resolution absorption measurements in premixed C_2H_4-air flame: Region II (5020 cm^{-1})



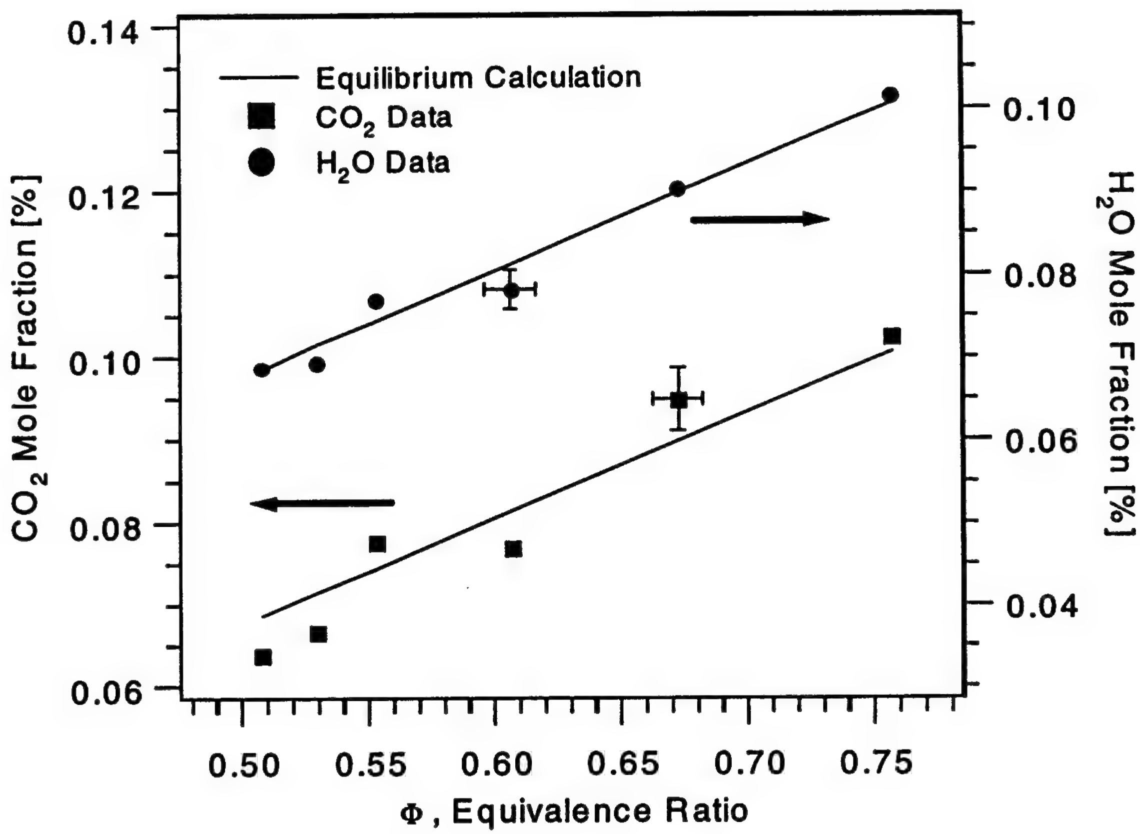
- **Measured 2-line ratio enables determination of T, H_2O (independent of CO_2)**

High-resolution absorption measurements in premixed C_2H_4-air flame: Region I



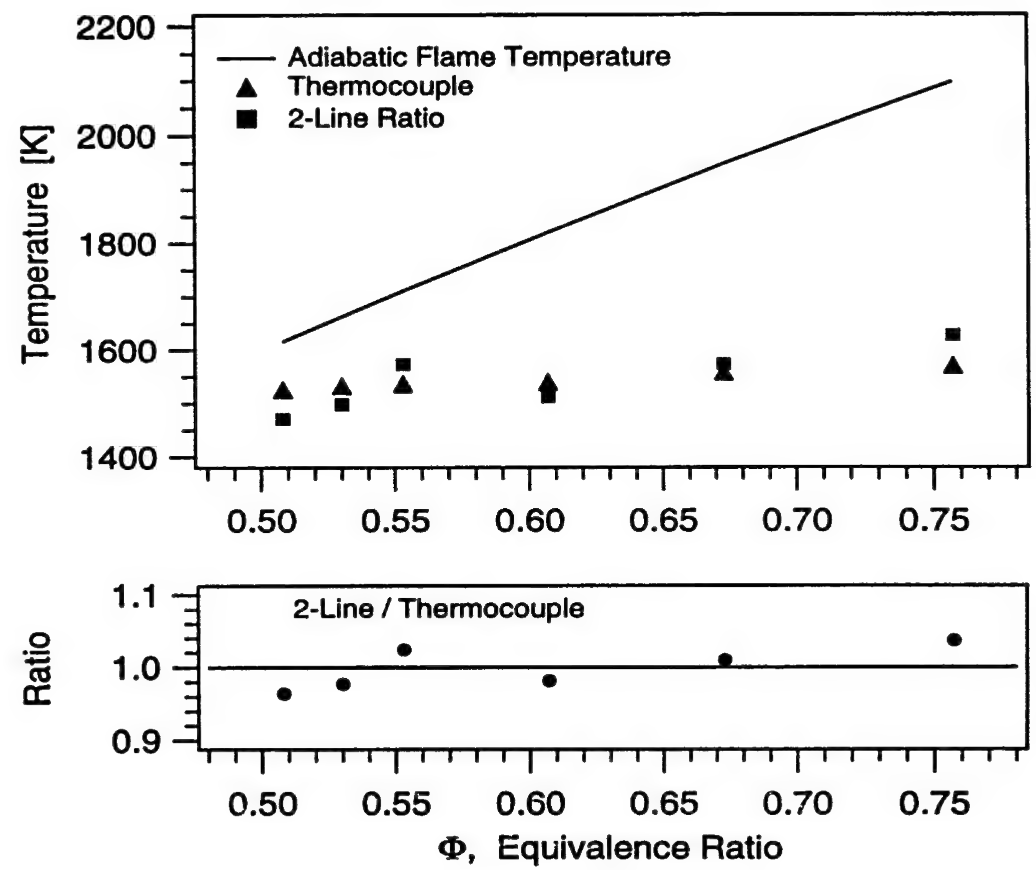
- Measurement of blended CO_2/H_2O feature yields CO_2
- CO_2 detection limit: 200 ppm-m (at 1500 K)

Measured CO_2 and H_2O mole fractions in premixed C_2H_4-air flame



- Good agreement between measured and calculated mole fractions (X_{H2O} to within 3%, X_{CO2} to within 6%)

In situ temperature measurements in premixed C_2H_4-air flame



- **Good agreement between laser and thermocouple temperature measurements (variation <6%)**

Summary

- Diode-laser sensors applied for control of T, X_{H_2O} in forced combustors (5-kW burner at Stanford; 50-kW burner at China Lake)
- Fast measurements (kHz rates) enable new control strategies
- Large coherent temperature oscillations (large T_{rms} values) in combustion region correspond to small CO exhaust emissions
- First *in situ* measurements of CO_2 (near 2 μm) demonstrate potential for multi-species concentration measurements

Ongoing / Future Work

- Extension of TDL to high-pressure flowfields
- New lasers (2.3, 2.7 μm) will enable sensitive CO, NO measurements

Acknowledgements

Senior Scientist:	Dr. D.S. Baer
Research Assistants:	E.R. Furlong R.M. Mihalcea M.E. Webber

Nonlinear Robust Controller Synthesis for Jet Engine Compression Systems

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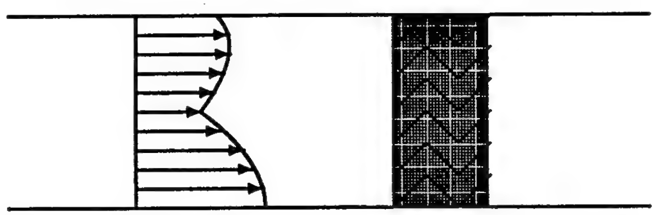
ARO Workshop on Intelligent Turbine Engines
Atlanta, Georgia
June 15-16, 1998

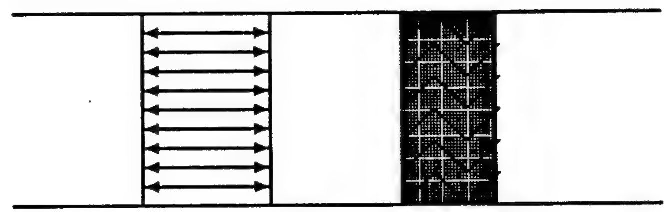
Outline

- Active Control Needs for Propulsion Systems
- Control Research Directions
  - Robust disturbance rejection control
  - Adaptive control
  - Nonlinear stabilization
    - Nonlinear gain scheduling, Extended linearization
  - Minimal complexity control
    - Fixed-structure control, Output feedback stabilization, Direct optimality
- Conclusions and Ongoing Research

Aerodynamic Instabilities of Rotating Stall and Surge



Circumferentially Nonuniform Flow

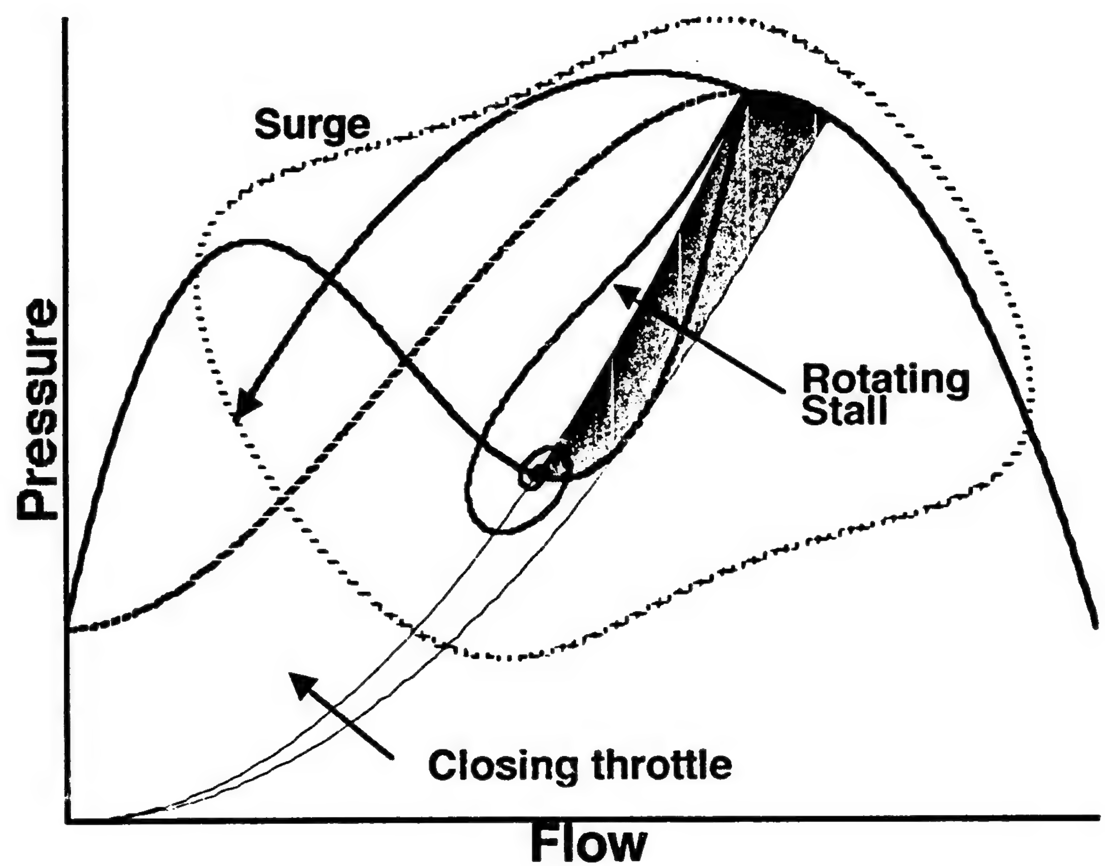


Axially Oscillating Flow

- **Rotating Stall**
  - Two-dimensional local compression system oscillation characterized by regions of flow that rotate at a fraction of the compressor rotor speed
  - Frequency $\approx$ 50–100 Hz

- **Surge**
  - One dimensional axisymmetric global compression system oscillation involving axial flow oscillations
  - Frequency $\approx$ 3–10 Hz

Rotating Stall and Surge Instabilities



Active Control for Compressor Instabilities I

- Compression system uncertainties (parametric and nonparametric)
  - Modeling errors
  - In-service changes due to aging
  - Manufacturing quality variations
  - Unmodeled dynamics
- Compression system disturbances (impulsive and persistent)
  - Transients
  - Inlet distortions (boundary layer separation)
  - Combustion noise (back-pressure disturbances)

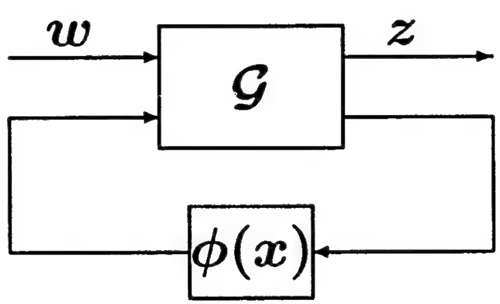
Active Control for Compressor Instabilities II

- System nonlinearities
  - Compressor performance map
  - Multiple equilibria
  - Limit cycles/Hysteresis
  - Actuator saturation
- Stringent performance goals necessitate design tradeoffs
  - High compression pressure/low power consumption $\longrightarrow$ increased operating efficiency
  - Rotating stall/surge/deep surge

Control Research Objectives

- Address compression system disturbances
  - Impulsive and bounded energy (L_2) disturbances
- Disturbance rejection controllers
- Address compression system uncertainties
  - Parametric uncertainties, unmodeled dynamics
- Robust-Adaptive controllers
- Minimize control law complexity
  - Output feedback controllers
  - Saturation controllers (amplitude and rate)

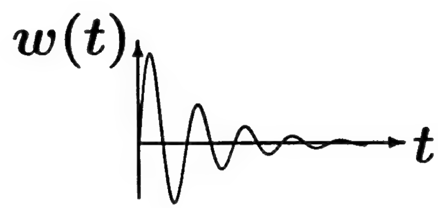
Disturbance Rejection Control

- 

$w \equiv$ Circumferential distortion, planar turbulence combustion disturbances

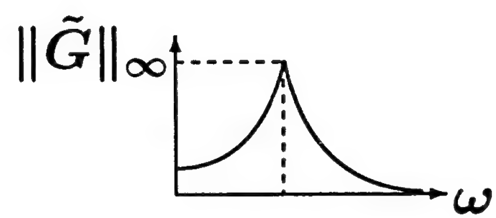
$z \equiv$ Rotating stall amplitude, pressure through compressor, flow through compressor

- $w(\cdot) \in \mathrm{L}_2 \quad \Longrightarrow$



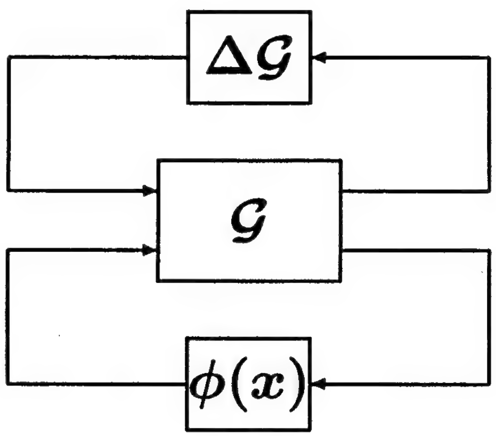
- $\|z(t)\|_{2,2} \leq \gamma \|w(t)\|_{2,2}$

- $\mathcal{G} = G(s) \quad \Longrightarrow \quad \|\tilde{G}(s)\|_\infty \leq \gamma$



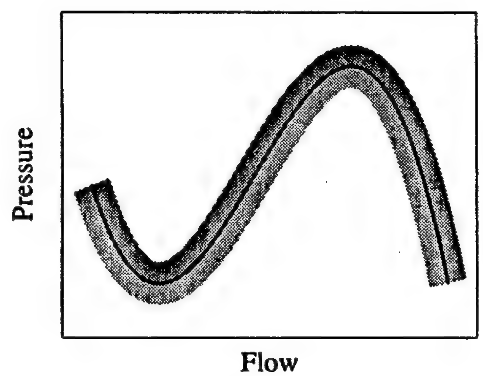
Nonlinear Robust Control

- Controller synthesis techniques for nonlinear systems with parametric uncertainty



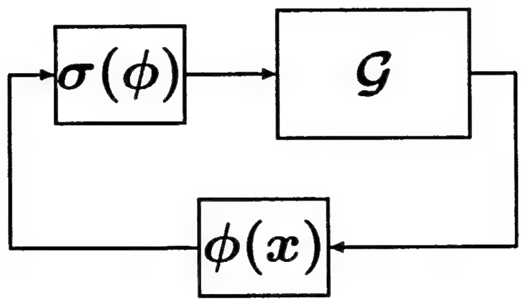
$\Delta\mathcal{G} \equiv$ system modeling uncertainty

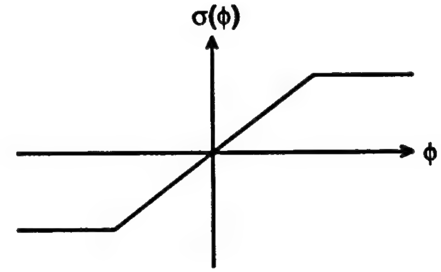
- $\phi(x)$ globally stabilizing for all $\Delta\mathcal{G}$



- Parametric uncertainty in the model
  - Uncertain compressor pressure-flow performance map

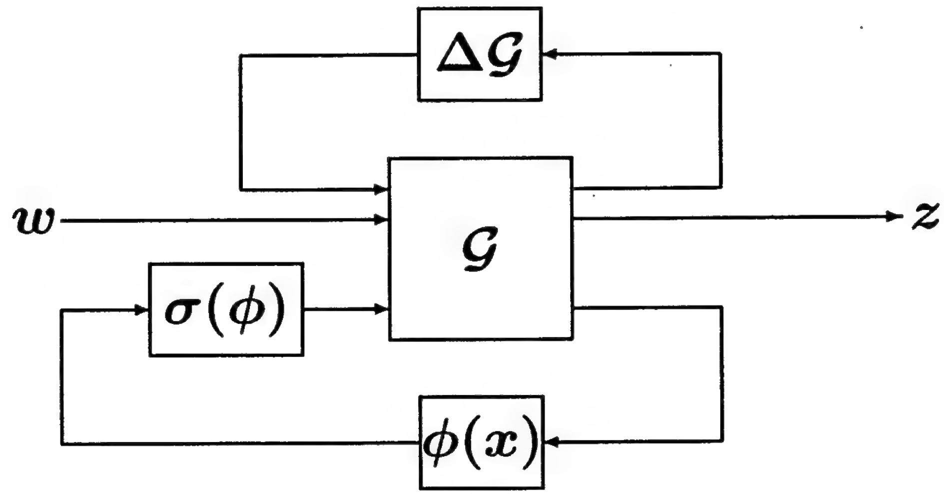
Saturation Control





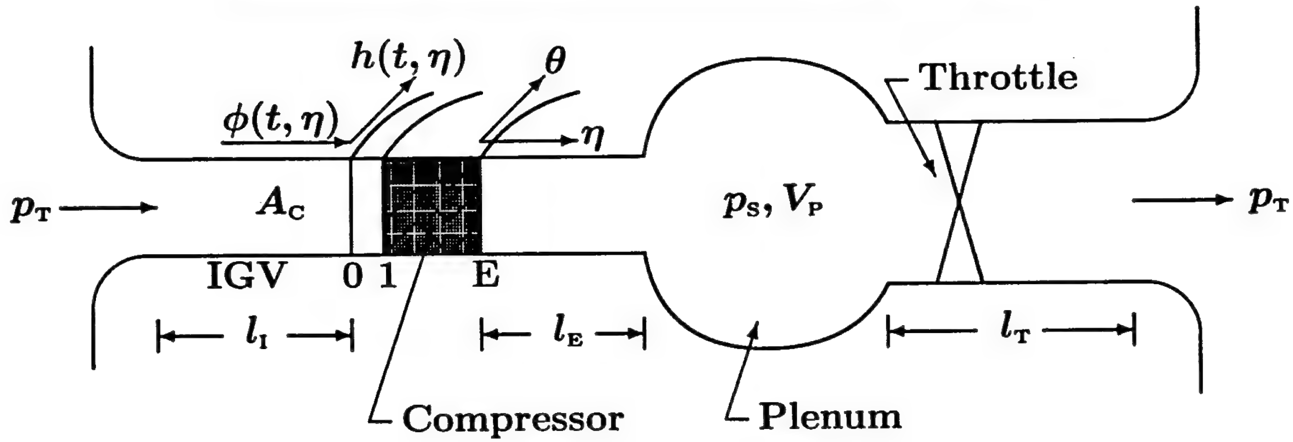
- $\sigma(\cdot)$ is a saturation nonlinearity
  - Can severely degrade closed-loop system performance
  - Can drive system to instability
- Rate saturation $\frac{\mathrm{d}\sigma(\phi)}{\mathrm{d}t}$
- Saturation controllers: $\phi(x)$ *globally* stabilizing for all $\sigma(\cdot)$
- $\sigma(\cdot) \equiv$ Compressor throttle opening constraint

Unified Robust Optimal Nonlinear Control Framework



- $\phi(x)$ globally stabilizing for all $\Delta\mathcal{G} \in \mathcal{F}$ and $\sigma \in \mathcal{M}$
- $\phi(x)$ is (inverse) optimal
- $\|z\|_{2,2} \leq \gamma \|w\|_{2,2}$ for all $\Delta\mathcal{G} \in \mathcal{F}$ and $w \in \mathrm{L}_2$
- Robust HJB theory
  - Robust control Lyapunov function guaranteeing *robust* stability is a solution to the HJB equation

Axial Compression System



- Negligible fluid velocity and acceleration in the plenum
  - Spatially uniform pressure in the plenum
- Incompressible, inviscid, and irrotational flow
  - Incompressibility assumption relaxed in the plenum
- Quasi-steady, axisymmetric compressor characteristic map

  $\Psi_{\rm cnom}(\Phi) = \Psi_{\rm c0} + 1 + \frac{3}{2}\Phi - \frac{1}{2}\Phi^3, \quad \Psi_{\rm C}(\Phi) = \Psi_{\rm cnom}(\Phi) + \Delta\Psi_{\rm c}(\Phi)$

  - $\Psi_{\rm C}(\Phi)$ is the compressor performance when the flow is circumferentially uniform and steady

Governing Fluid Dynamic Equations

- Governing fluid dynamic equations

$$
\begin{aligned}
\dot{A}(t) &= \frac{\sigma}{2}A(t)\left(1-\Phi^2(t)-\frac{A^2}{4}(t)\right), & A(0) = A_0 \quad t \geq 0 \\
\dot{\Phi}(t) &= -\Psi(t)+\Psi_{\mathrm{c}}(\Phi(t))-\frac{3}{4}\Phi(t)A^2(t), & \Phi(0) = \Phi_0 \\
\dot{\Psi}(t) &= \frac{1}{\beta^2}(\Phi(t)-\Phi_{\mathrm{T}}(t)), \quad \Psi(0) = \Psi_0 & \\
\dot{r}(t) &= \text{constant} &
\end{aligned}
$$

- A is the normalized stall cell amplitude
- Φ is the axial mass flow in the compressor
- Ψ is the total-to-static pressure rise
- r is the stall cell phase
- Φ_{T} is the mass flow through the throttle
- β is the compliance coefficient (rotor speed, plenum size)

Nonlinear Uncertain State Space Model

- Transformed fluid dynamic equations

$$\begin{aligned}
\dot{A}(t) &= -\tfrac{\sigma}{2}A(t)[\tfrac{A^2}{4}(t) + 2\Phi_s(t) + \Phi_s^2(t)] + \Delta f_1(A, \Phi_s), \quad t \geq 0 \\
\dot{\Phi}_s(t) &= -\tfrac{3}{2}\Phi_s^2(t) - \tfrac{1}{2}\Phi_s^3(t) - \tfrac{3}{4}A^2(t)[1 + \Phi_s(t)] \\
&\quad -\Psi_s(t) + \Delta f_2(A, \Phi_s) \\
\dot{\Psi}_s(t) &= -u(t) \\
A(0) &= A_0, \quad \Phi_s(0) = \Phi_{s0}, \quad \Psi_s(0) = \Psi_{s0}
\end{aligned}$$

- Uncertain dynamical system

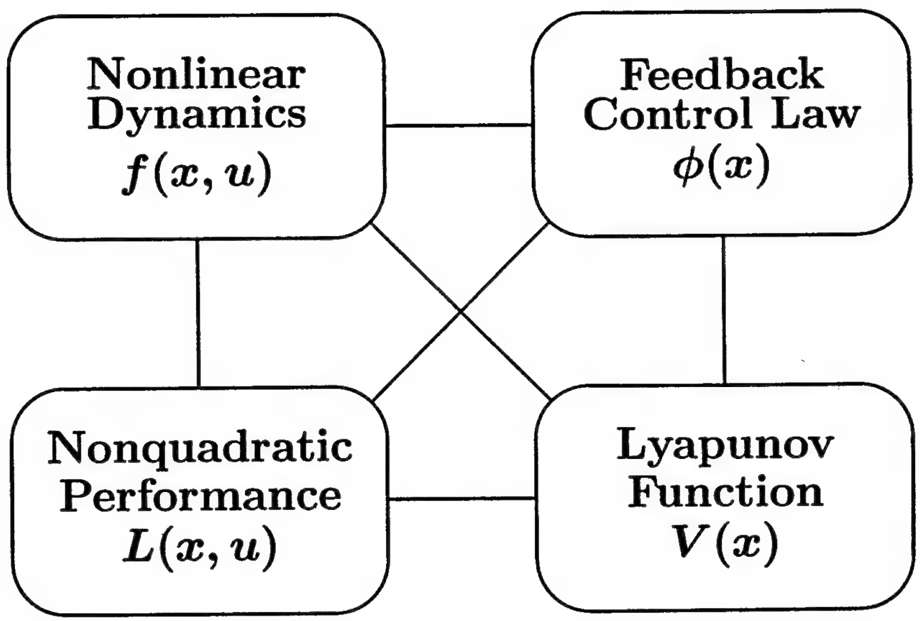
$$\begin{aligned}
\dot{x}(t) &= f_0(x(t)) + \Delta f(x(t)) + g_0(x(t))\hat{x}(t) + J_1(x(t))w(t) \\
\dot{\hat{x}}(t) &= u(t) + J_3(\hat{x}(t))w(t) \\
x(0) &= x_0, \quad \hat{x}(0) = \hat{x}_0, \quad \Delta f \in \mathcal{F}, \quad t \geq 0
\end{aligned}$$

Unification Between HJB and Lyapunov Stability Theory

- Optimality, robust stability, and performance

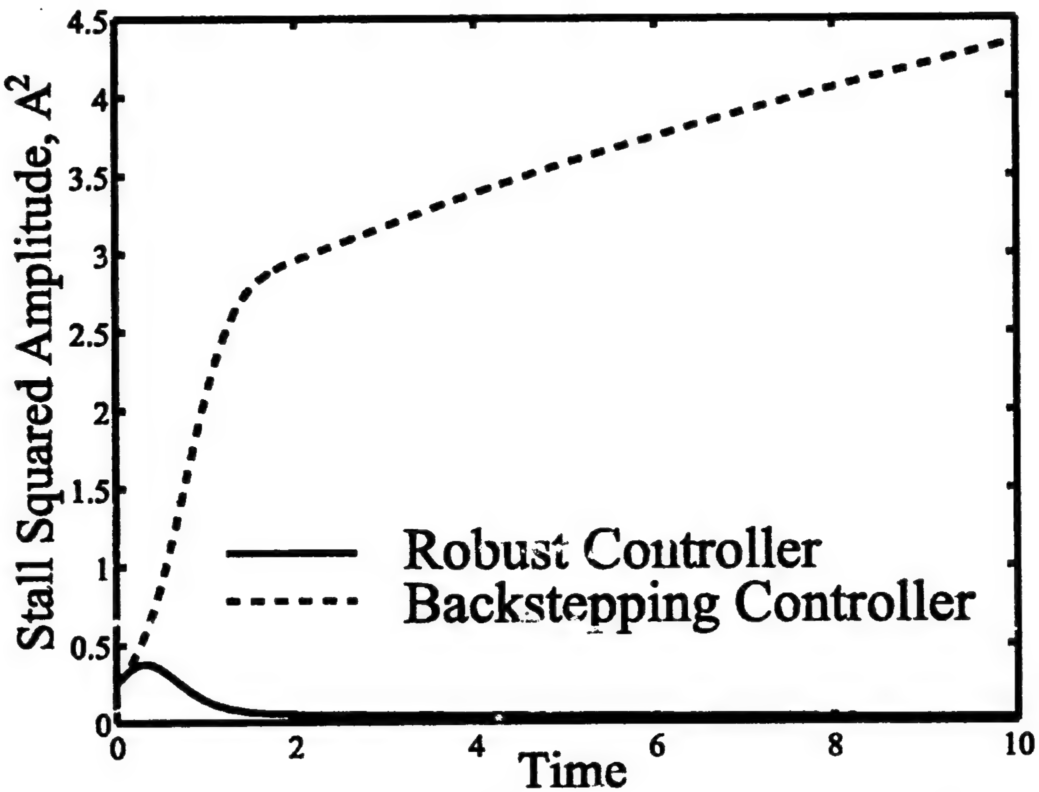
- Solution of HJB equation is a control Lyapunov function

- Yields nonlinear feedback control law



Globally Stabilizing Robust Control for Rotating Stall and Surge I

- $A_0 = 0.5, \quad \Phi_{s0} = -0.25, \quad \Psi_{s0} = 0, \quad \Psi_{c0} = 0.72$
- Squared stall amplitude versus time



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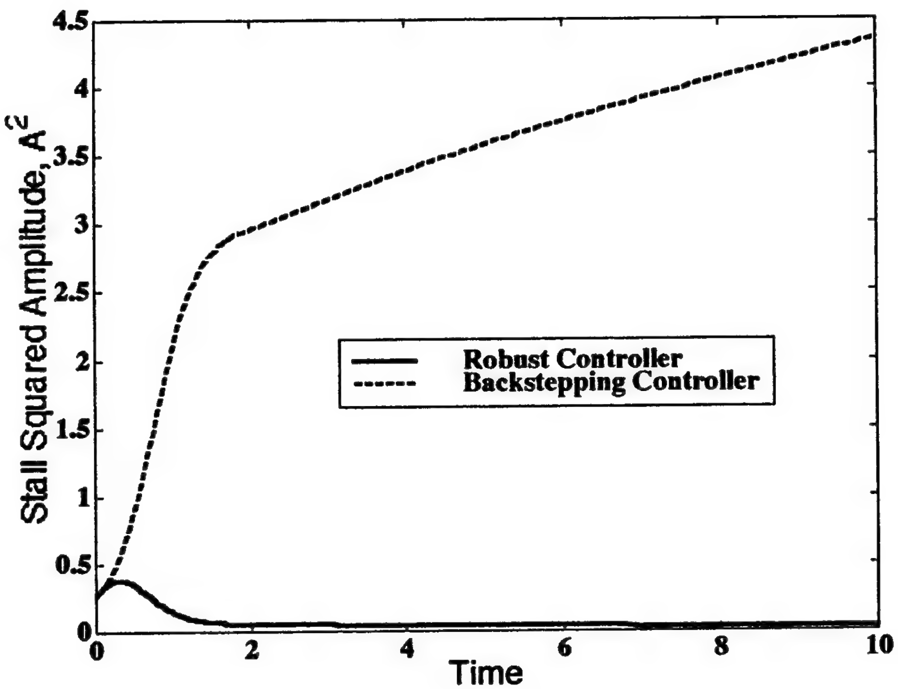
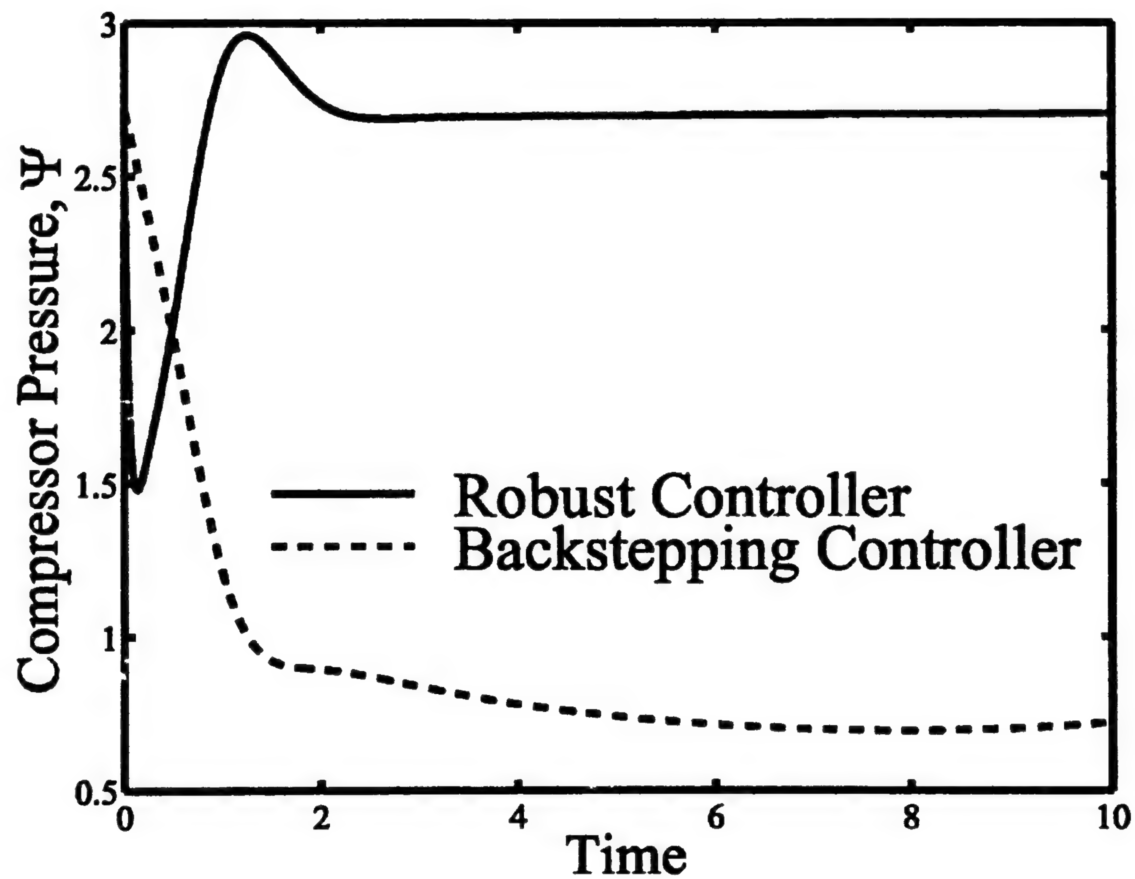


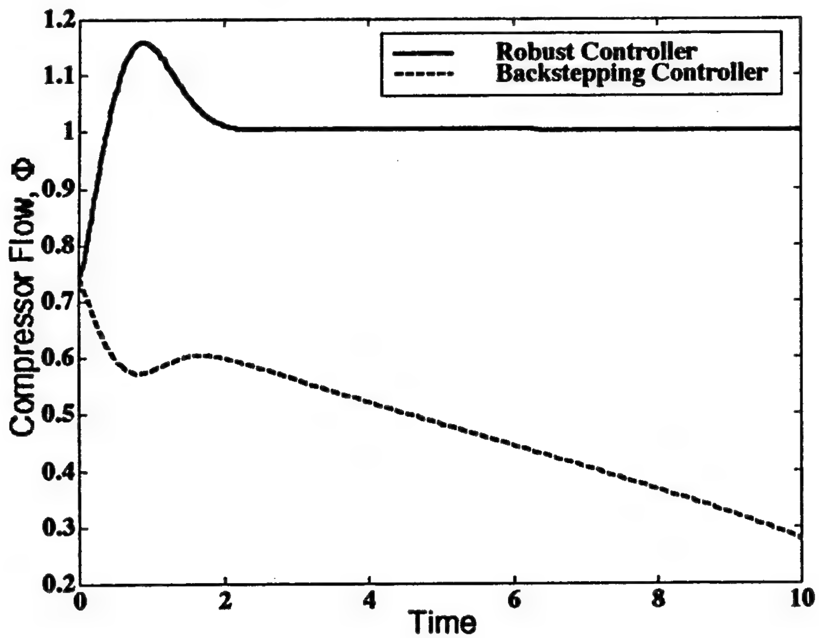
Globally Stabilizing Robust Control for Rotating Stall and Surge II

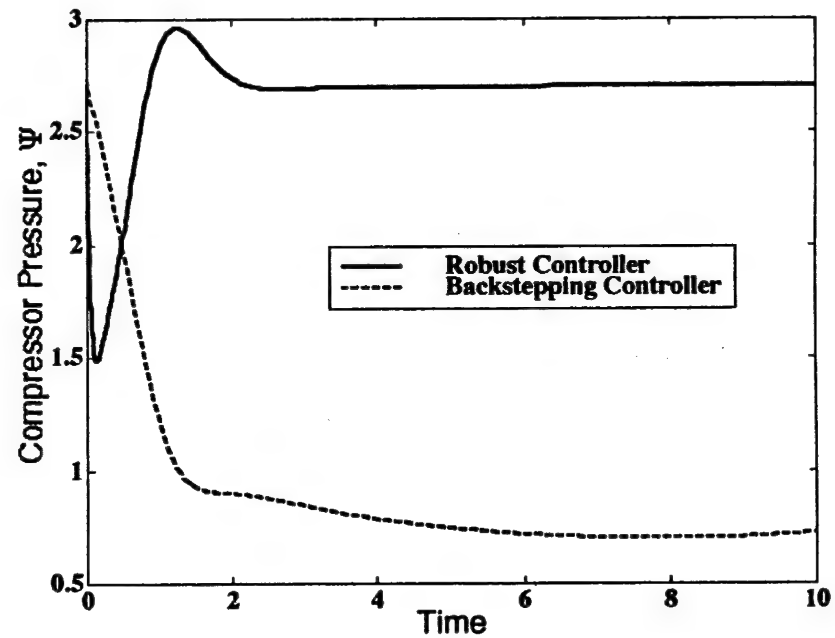
- Compressor pressure versus time



Globally Stabilizing Robust Control for Rotating Stall and Surge II

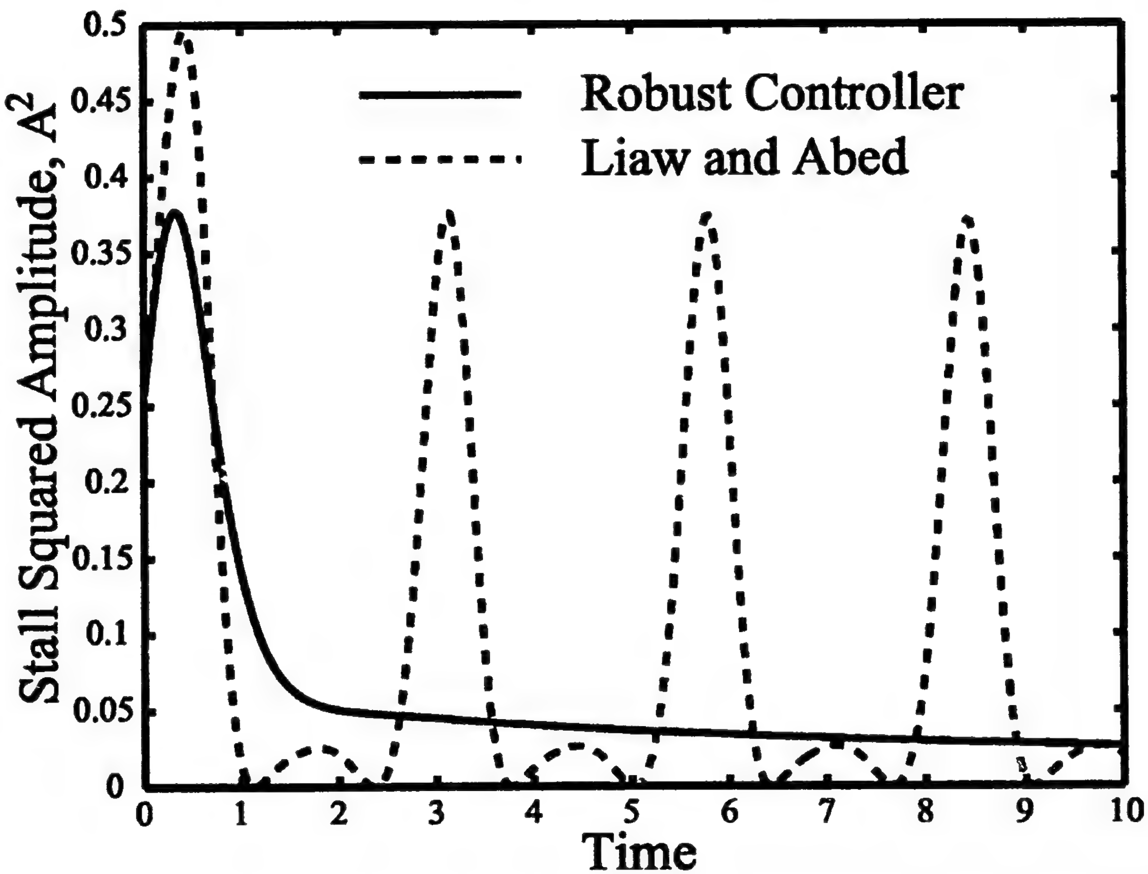
- Compressor flow and pressure versus time





Bifurcation - Based Controllers I

- Liaw and Abed Controller: $\gamma_{\text{throt}}(A) = \gamma_0 + kA^2$
- No guarantees of global stability or robustness



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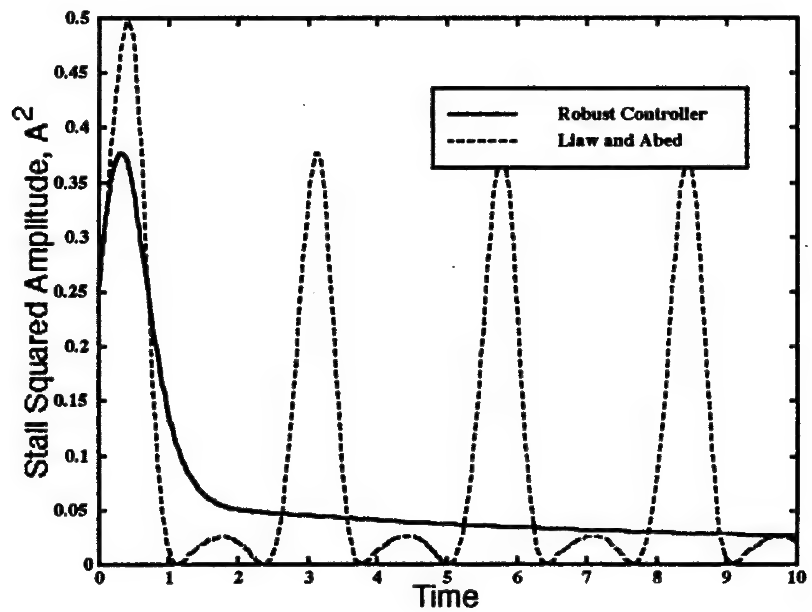
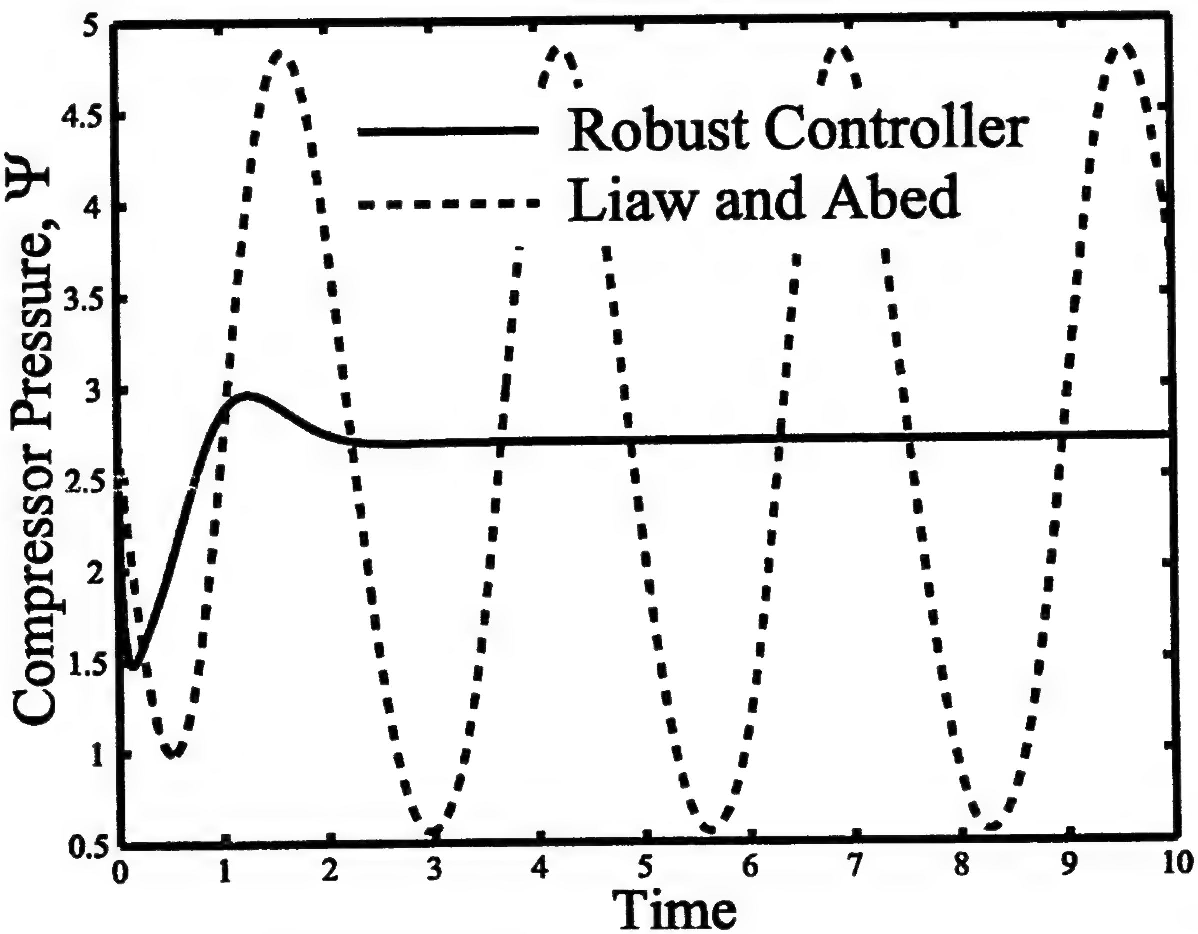


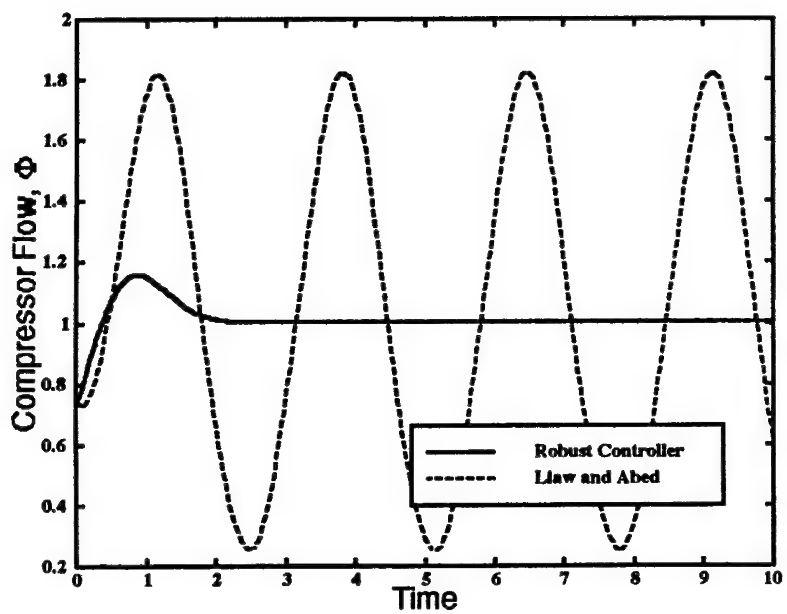
Bifurcation - Based Controllers II

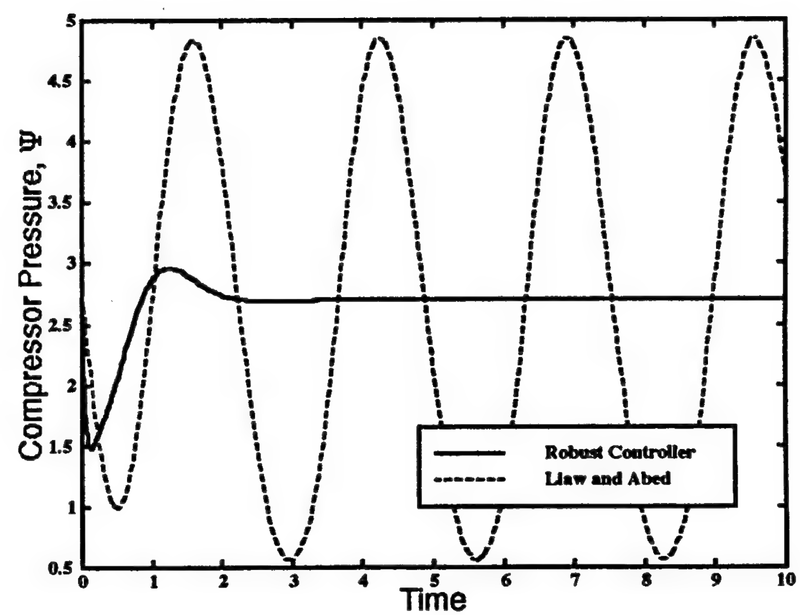
- Compressor pressure versus time



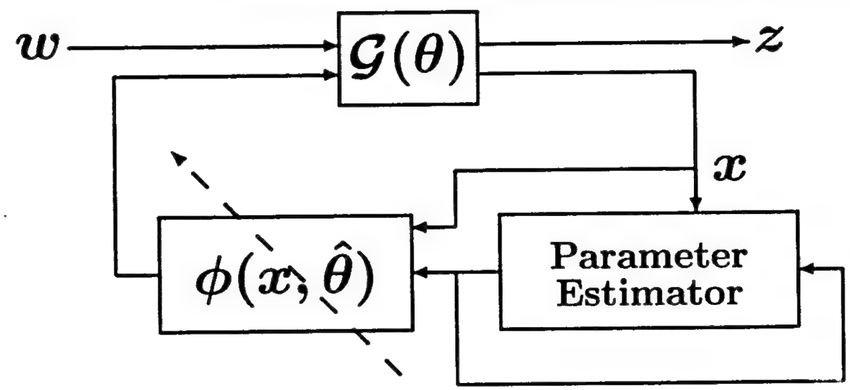
Bifurcation - Based Controllers II

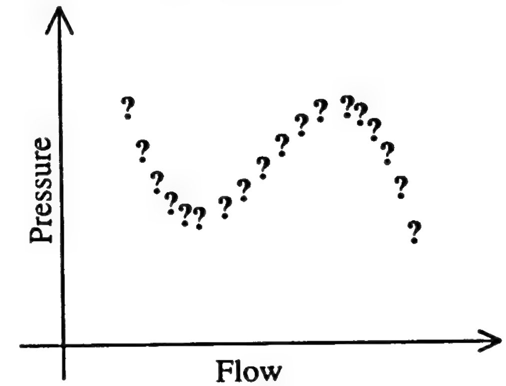
- **Compressor flow and pressure versus time**





Optimal Adaptive Control Problem

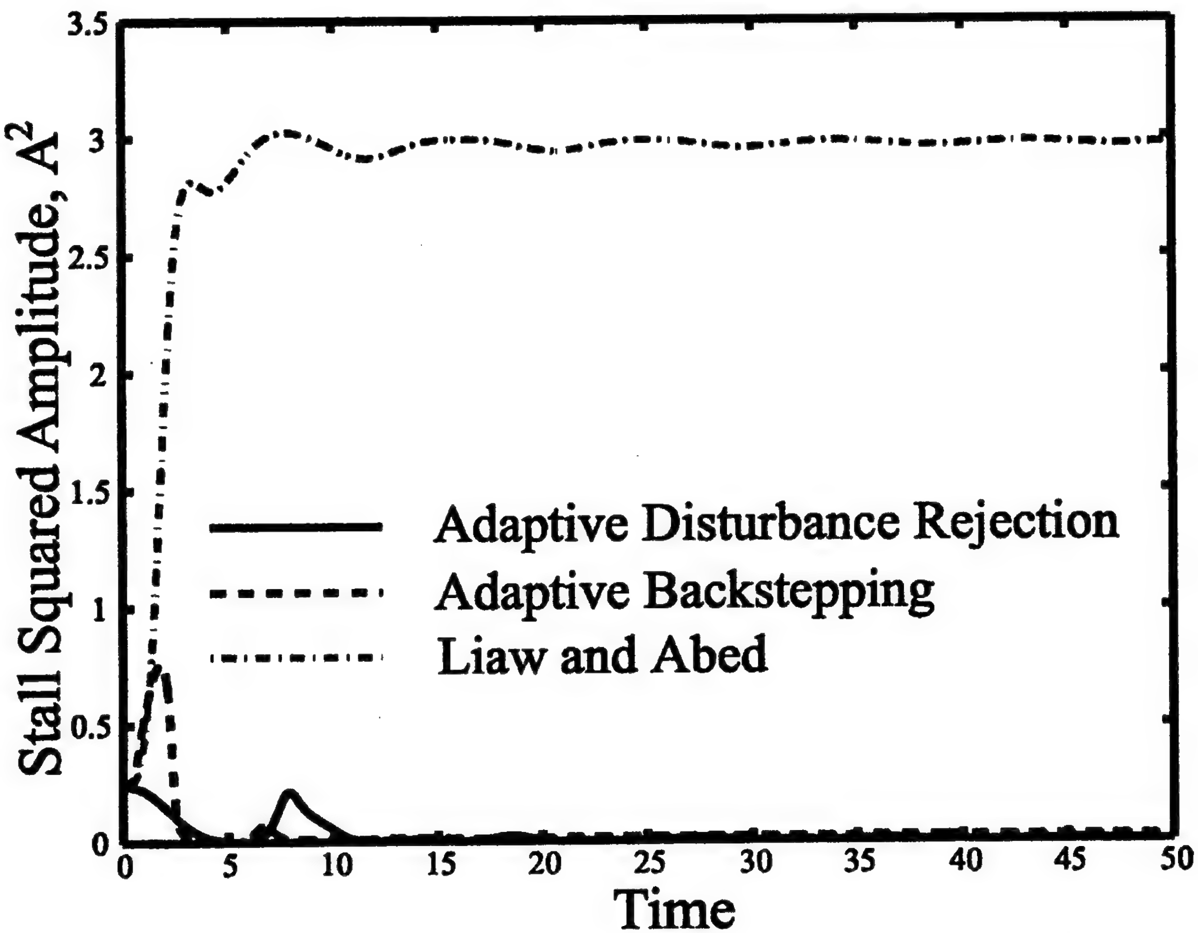




- Parameter update law
  - Identify unknown system parameters
  - Adjust feedback gains to account for system variation
- Optimality-based framework
  - Parametric robustness, disturbance rejection, robustness to unmodeled dynamics
  - Known uncertainty structure but unknown variation
  - Compressor flow map modeled by orthonormal polynomials
  - $(x(t), \hat{\theta}(t)) \rightarrow \mathcal{M} \triangleq \{(x, \hat{\theta}) : x = 0, \dot{\hat{\theta}} = 0\}$ as $t \rightarrow \infty$

Adaptive Control for Rotating Stall and Surge I

- Squared stall cell amplitude versus time



Adaptive Control for Rotating Stall and Surge I

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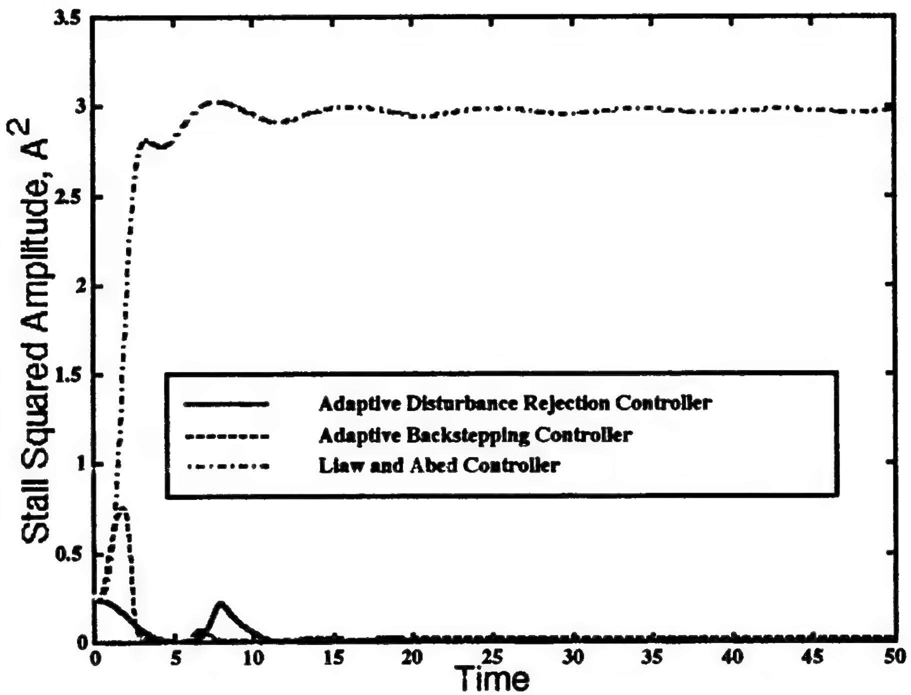
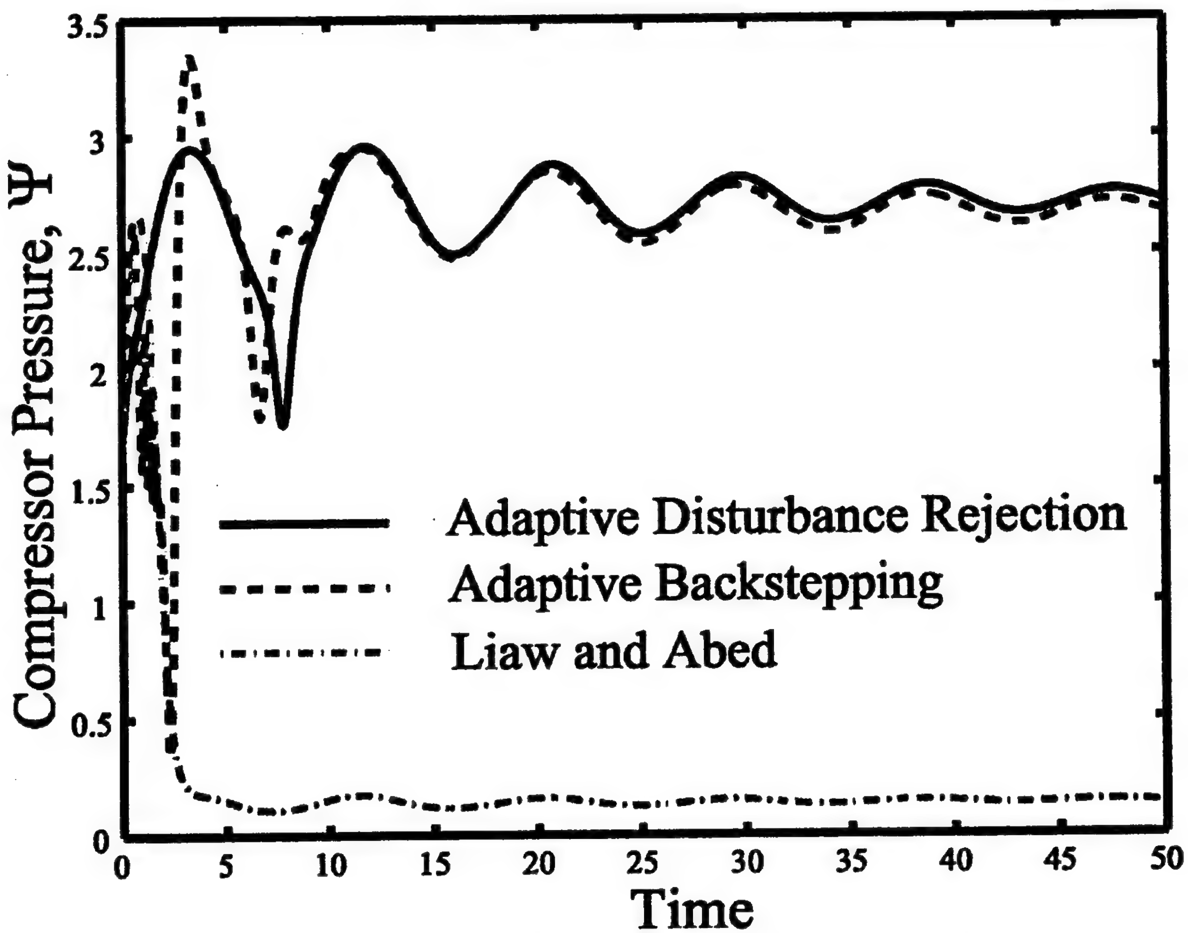


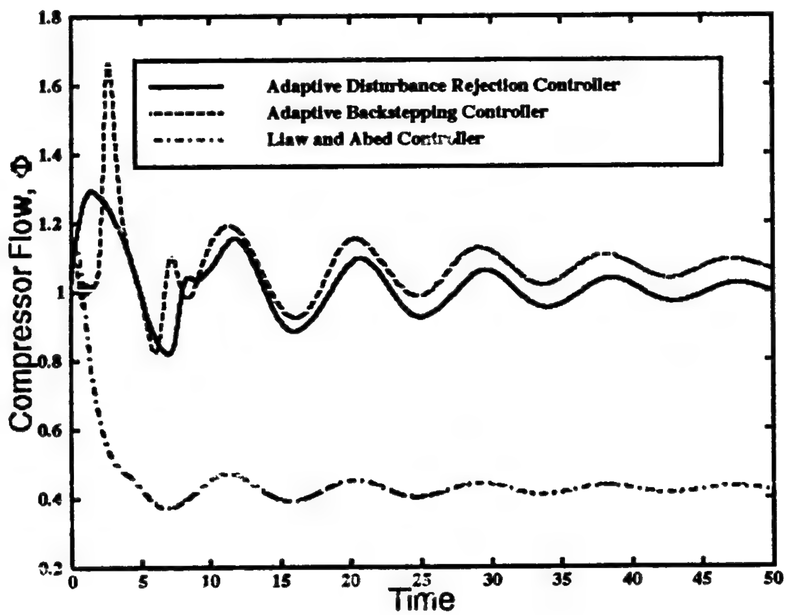
Adaptive Control for Rotating Stall and Surge II

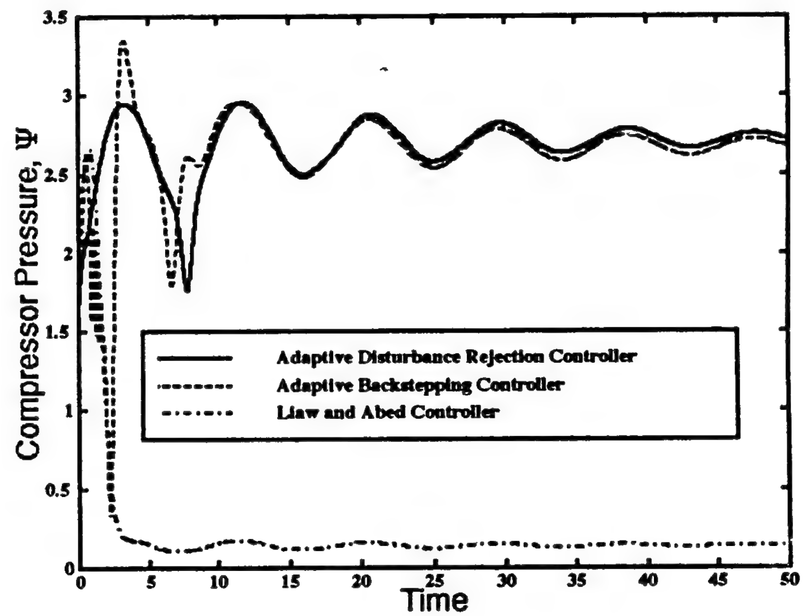
- Compressor pressure versus time



Adaptive Control for Rotating Stall and Surge II

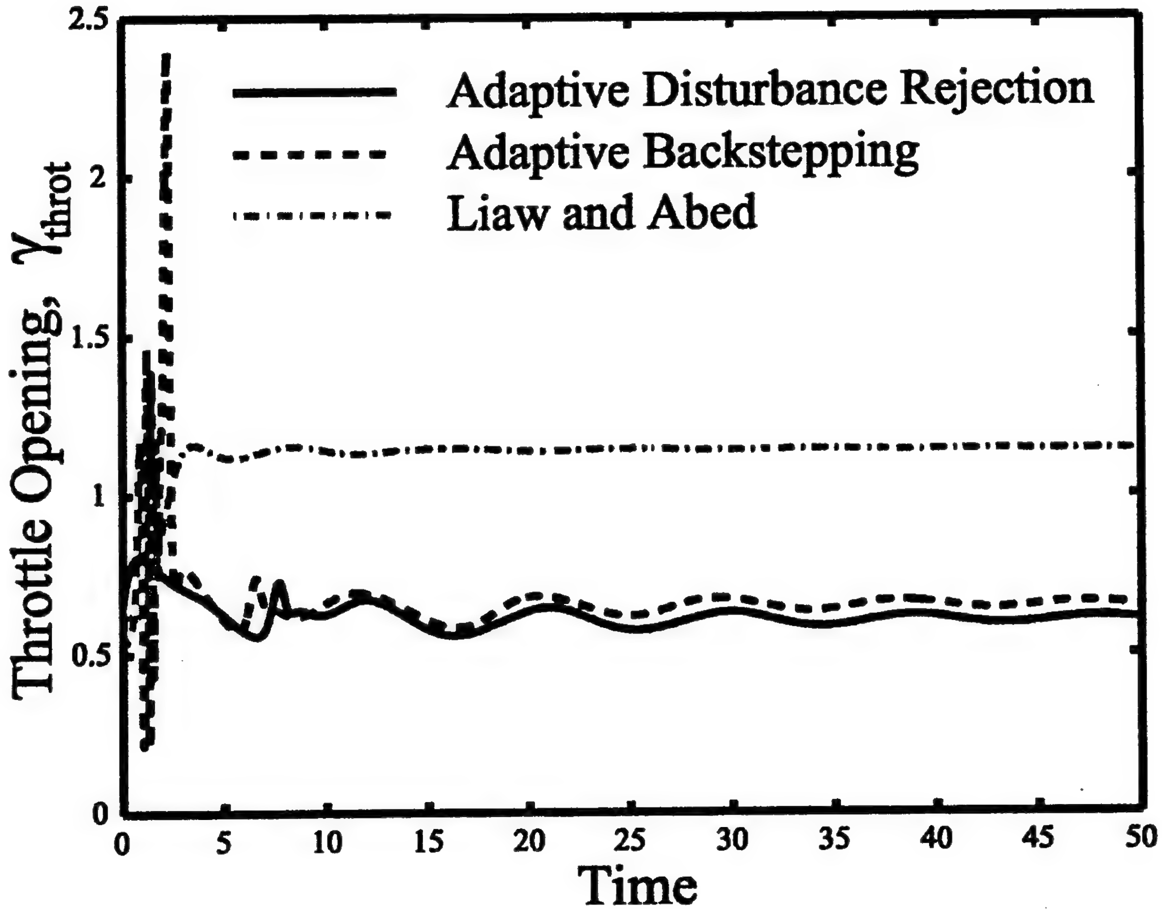
- Compressor flow and pressure versus time





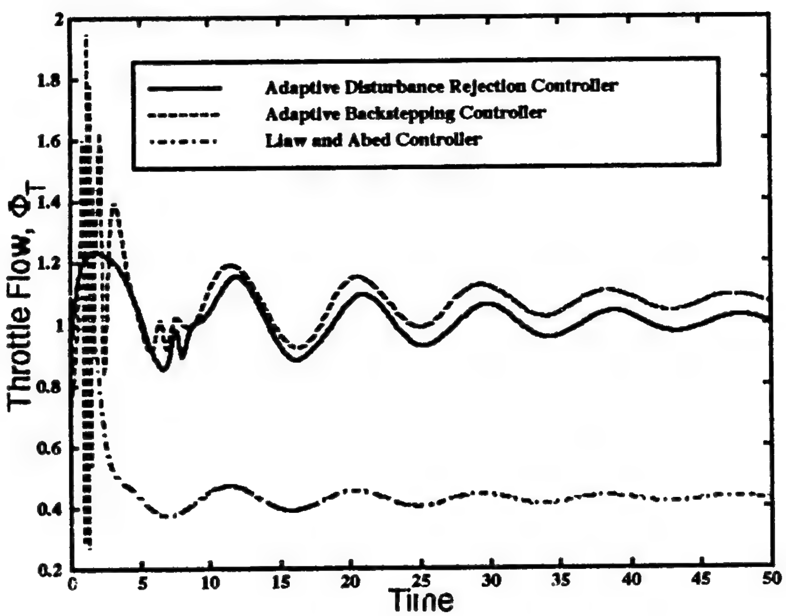
Adaptive Control for Rotating Stall and Surge III

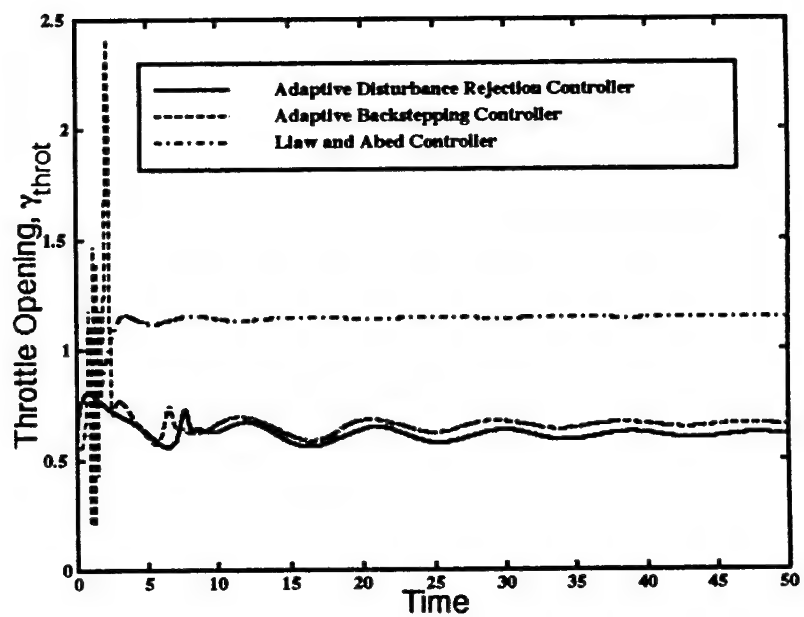
- Control effort versus time



Adaptive Control for Rotating Stall and Surge III

- Control effort versus time



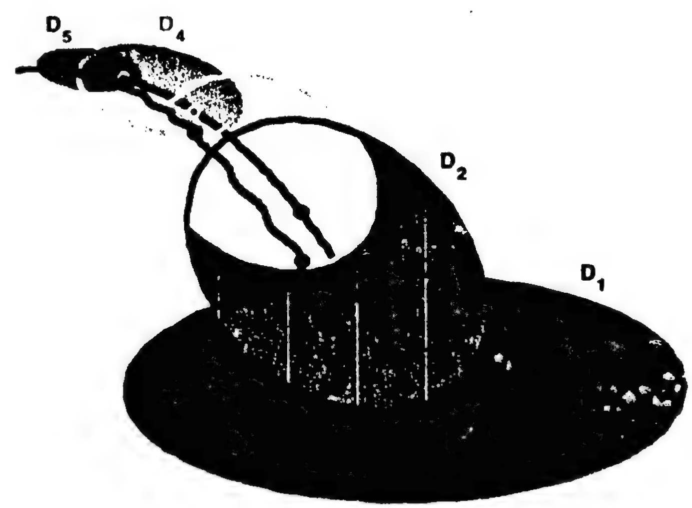


Multi-Mode Control

- Higher-order disturbance velocity potential harmonics are strongly coupled with the first harmonic during stall inception
- Not all nonlinear phenomena can be captured with a low-order model (e.g., bifurcations, limit cycles, hysteresis, etc.)
- Difficulties in applying bifurcation-based and backstepping controllers to high-order models
  - Bifurcation diagrams involve more complicated phenomena (e.g., fold and Hopf branches)
  - High-order subsystem dynamics
- Develop a *global* control strategy for multi-mode axial flow compressors

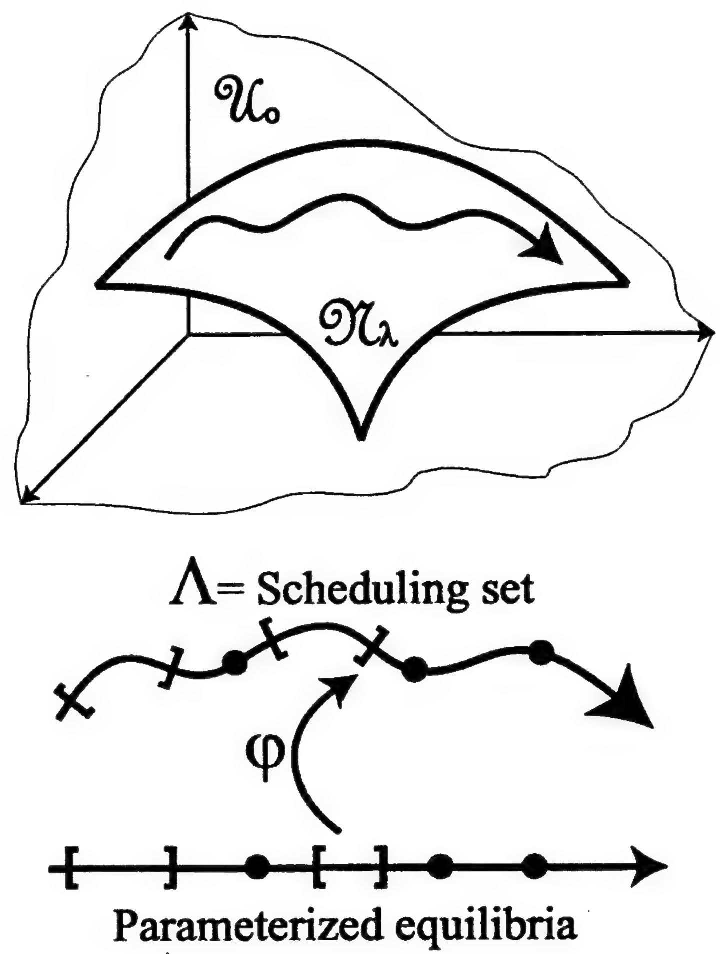
Nonlinear System Stabilization for Multi-Mode Compressor Models

- A *Novel* Lyapunov-based nonlinear control framework
  - Guarantees stability for a parameterized set of system equilibria
  - Compressor problem: Stable equilibrium branch of the axisymmetric compressor characteristic map
- Equilibria-dependent Lyapunov functions
  - Nonlinear control strategy
  - Converging domains of attraction
  - $\mathcal{D} = \cup \mathcal{D}_\lambda$



Nonlinear System Stabilization

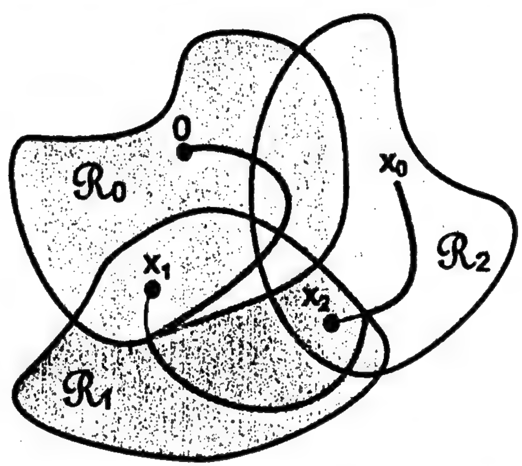
- Piecewise continuous and continuous control laws
  - Isolated point topology versus a homotopic continuum topology
- Provides theoretical foundation for designing gain scheduled controllers
  - Guarantees stability over a range of system operating conditions
  - Global stability

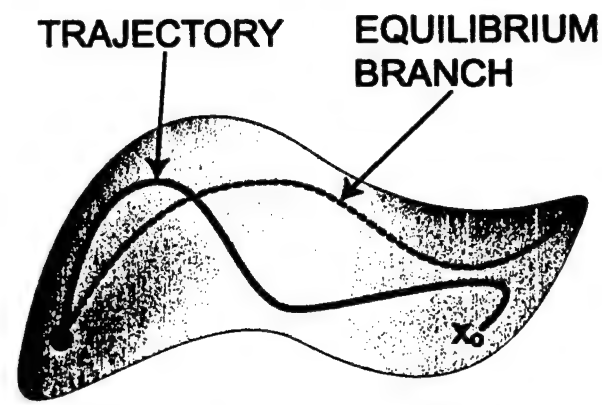


Feedback Control Strategy

- Construct stabilizing controllers $u_\lambda(x)$ for all $x_0 \in \mathcal{R}_\lambda$

- Overall feedback control $u(t) = u_{\lambda_\Lambda(x(t))}(x(t))$ stabilizes $\mathcal{R}_0$ for $x_0 \in \mathcal{R}$



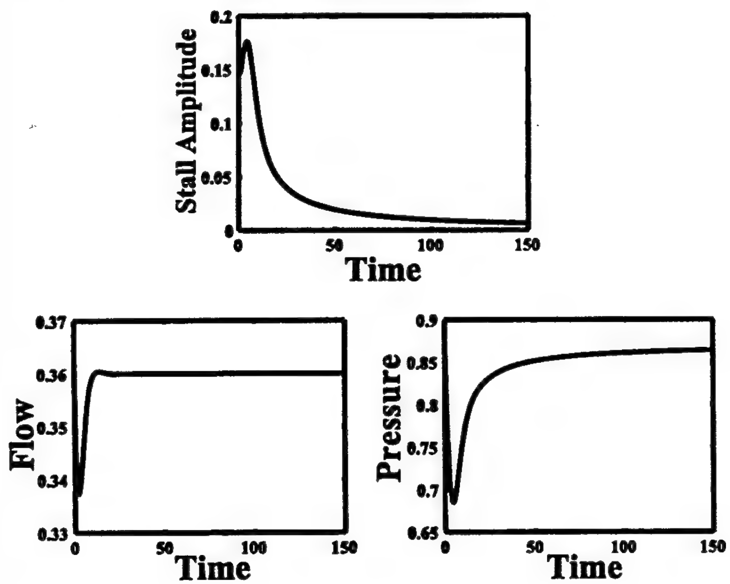


- $V(x)$ is a nonincreasing lower semicontinuous function of time

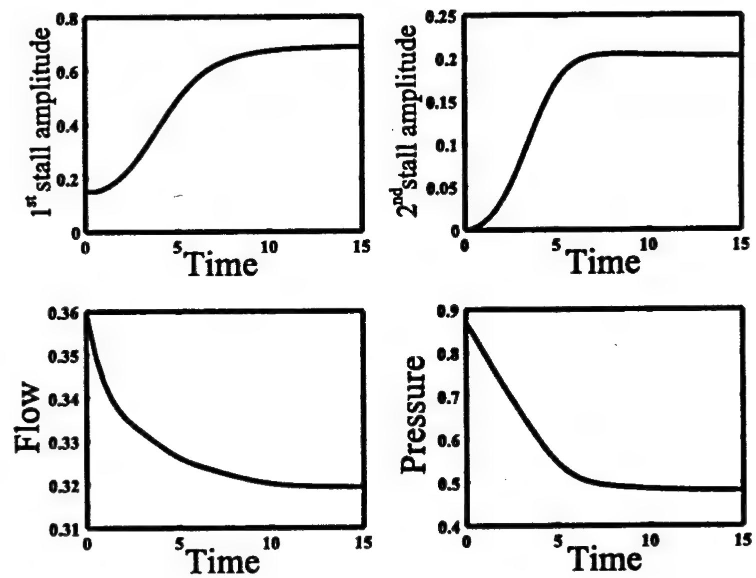
- There exists $\{t_k\}_{k=0}^{\infty}$ such that $V(x(t_{k+1})) < V(x(t_k))$

Backstepping Controller Design

- *Globally* stabilizing backstepping controller for a one-mode model given by Krstić *et al.*, 1995

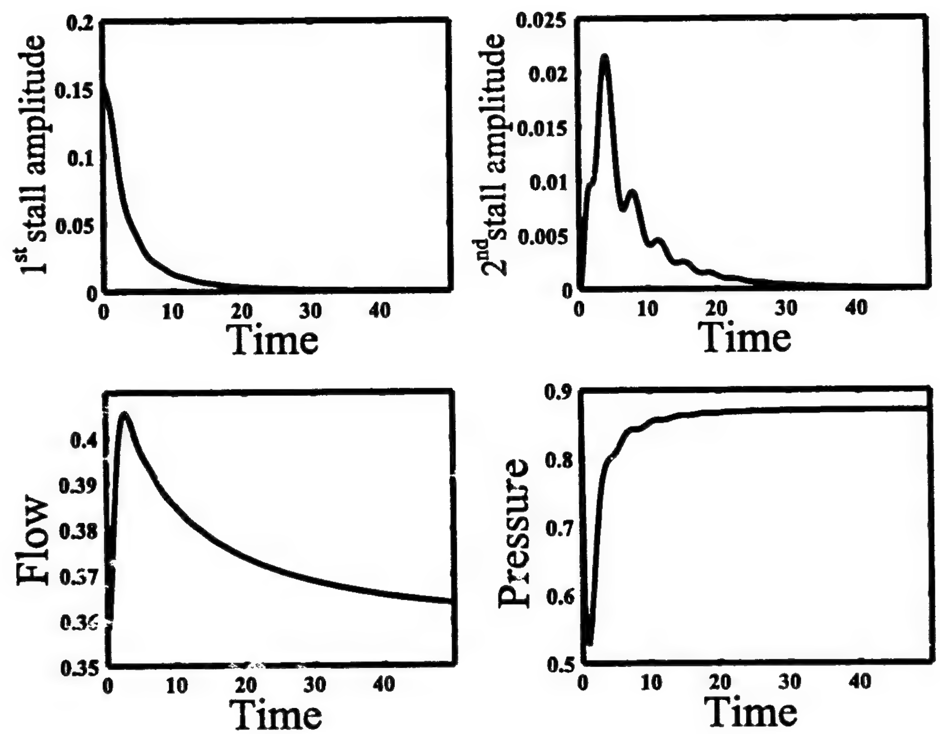


- In the two-mode case the backstepping controller drives the system to a stalled equilibrium



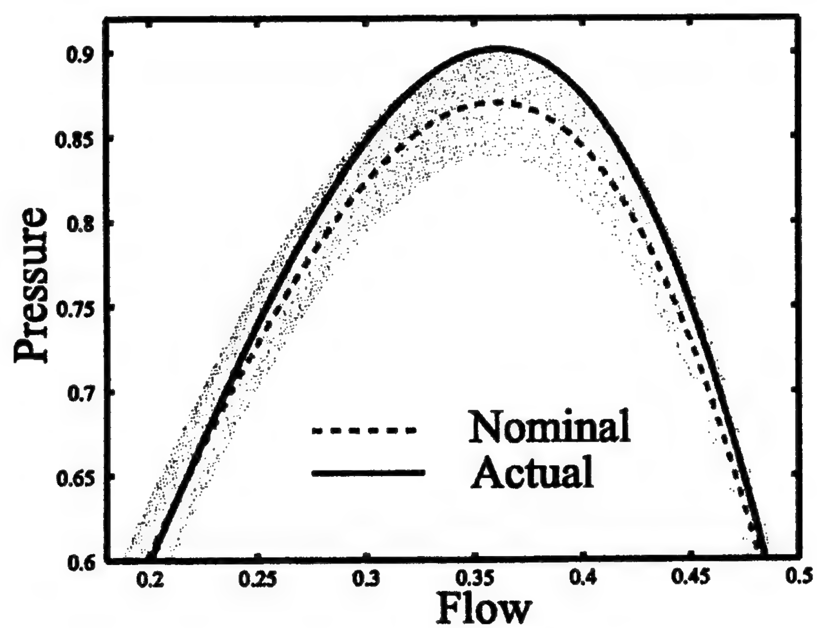
Globally Stabilizing EDLF Controller

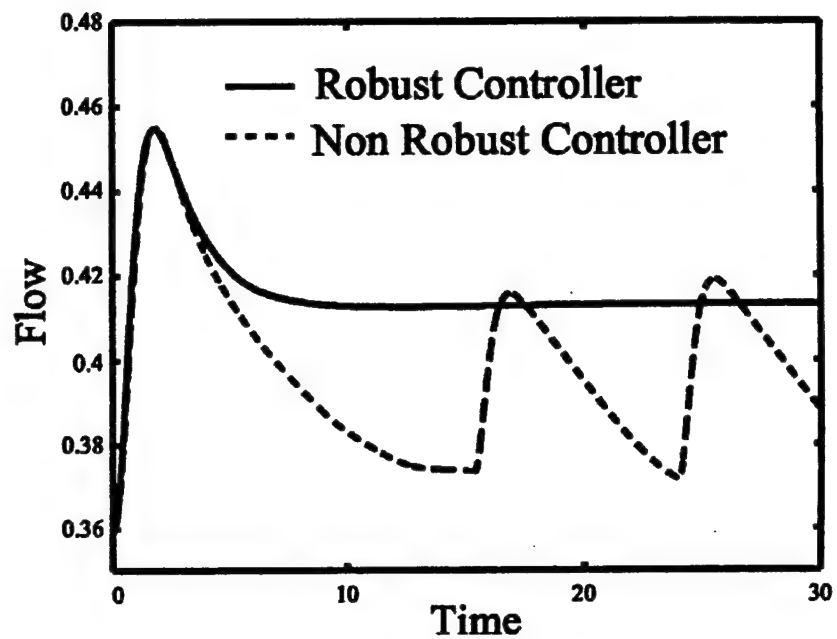
- The EDLF controller guarantees global stability for an arbitrary number of modes
- In the two-mode case



Robust Globally Stabilizing EDLF Controller

- The robust EDLF controller stabilizes an invariant set containing the maximum pressure point when the compressor characteristic is uncertain
- Perturbed compressor pressure-flow map





Robust Globally Stabilizing EDLF Controller

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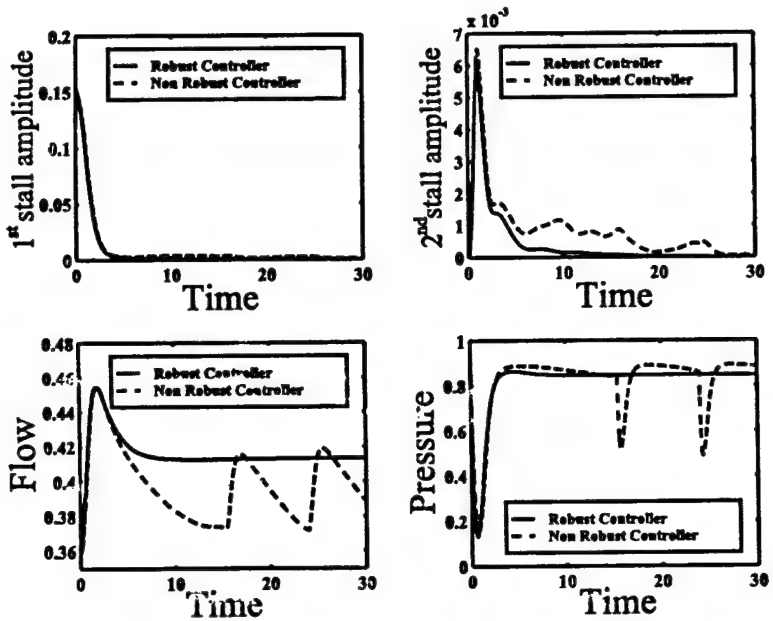
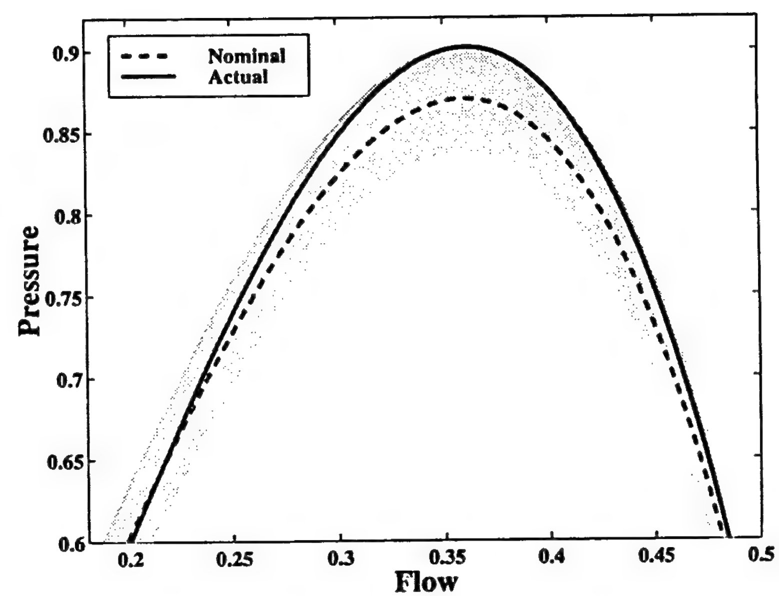
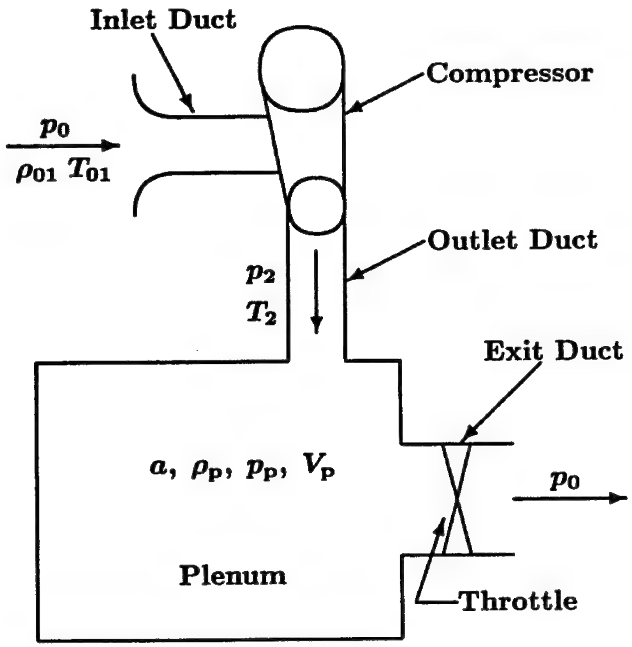
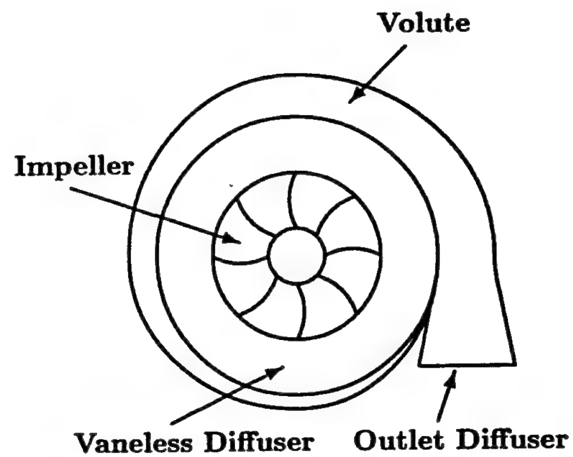




Centrifugal Compressor Modeling and Control

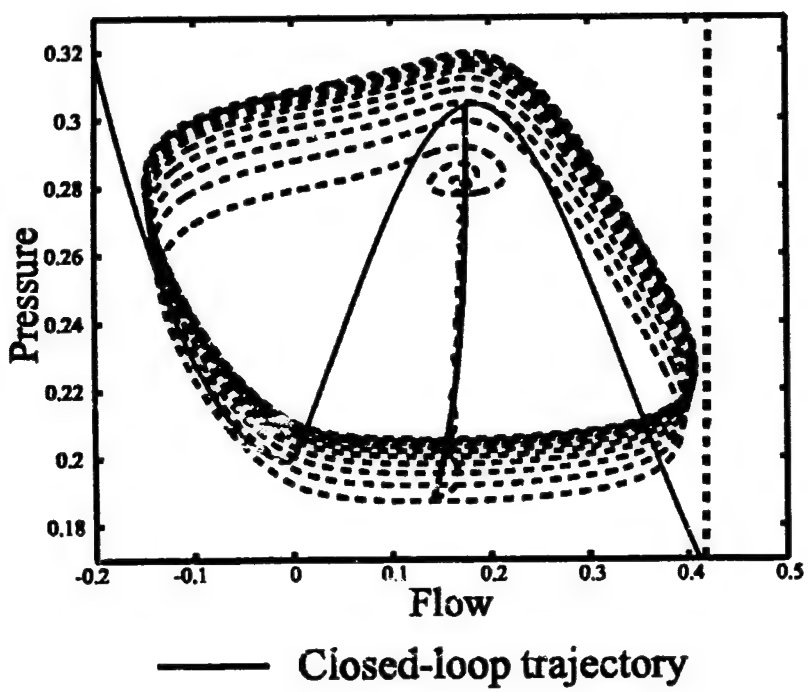


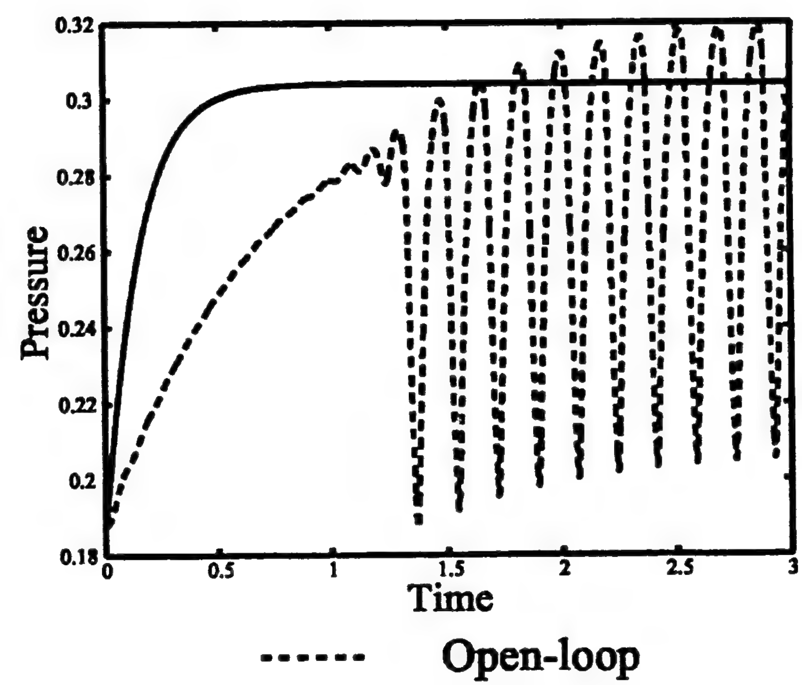


- Centrifugal compressor model for surge control
  - Three state model, pressure, mass flow, impeller angular velocity
  - Conservation of mass and momentum, turbocharger spool dynamics
  - Compressor pressure-flow map is a surface
  - Lyapunov-based control design

Globally Stabilizing Controller

- Controlled and uncontrolled phase portrait of pressure-flow state trajectories from 20,000 rpm to 25,000 rpm





Globally Stabilizing Controller

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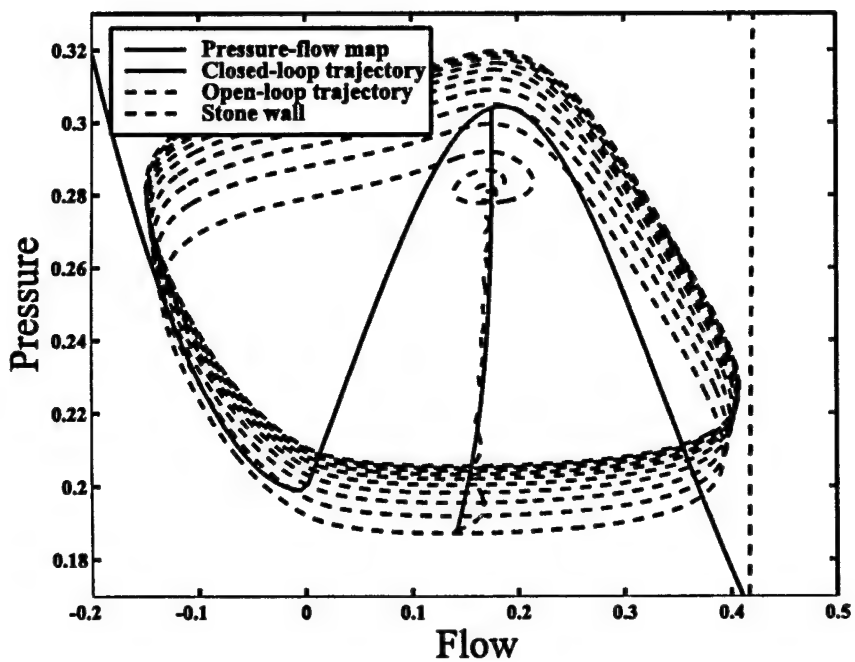
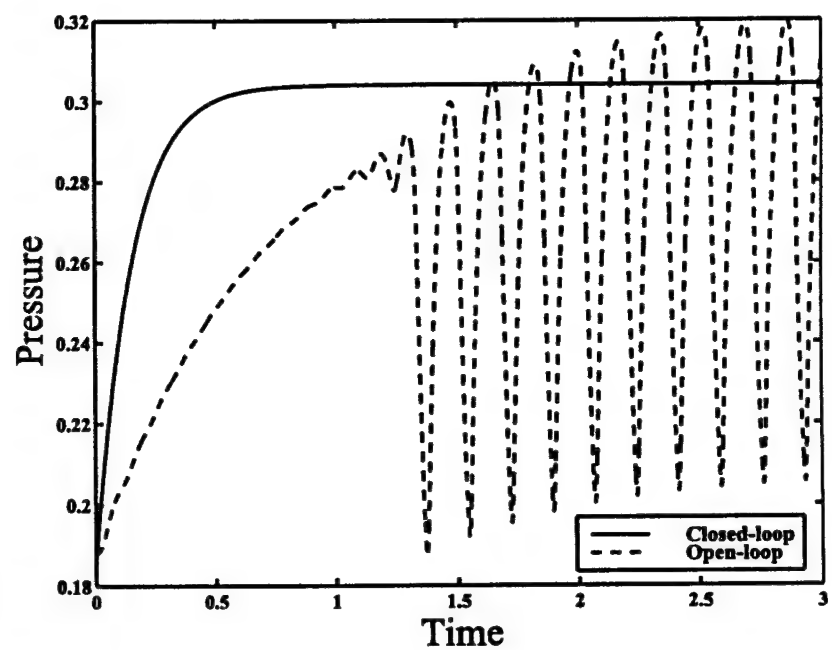
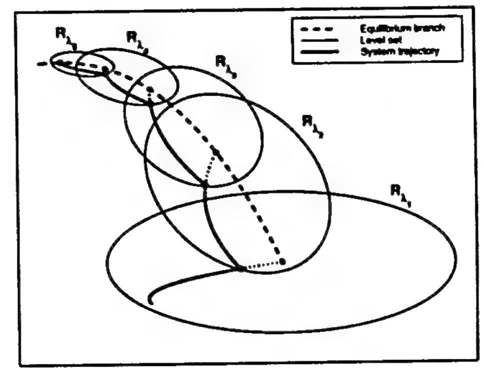


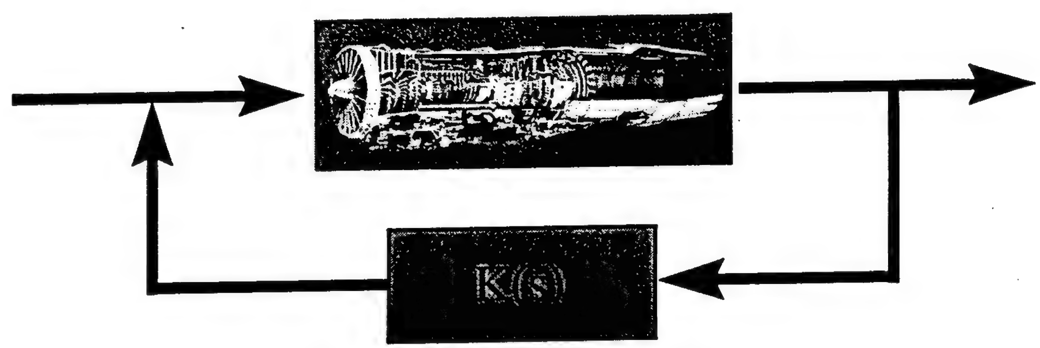


Ongoing Research



- Nonlinear system stabilization
  - Amplitude and rate saturation constraints
  - Dynamic compensation extensions
- Differential inclusions
  - Extended linearization via polytopic LDI's
  - Nonlinear *dynamic output* feedback
  - Direct optimality
- Fixed-structure nonlinear control
  - Minimize controller complexity
  - Fix the structure of the CLF
  - Nonlinear output feedback controllers and direct optimality
- Controller implementation

Active Combustion Control for Future Aircraft Engines



Goals and Technologies for Tomorrow's Gas Turbines
Georgia Tech., June 15-16 1998

Dr. Sanjay Garg
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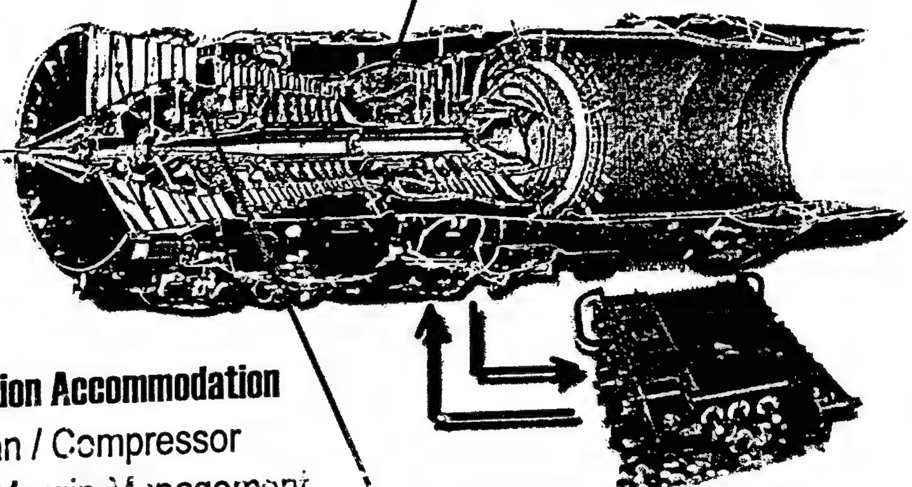
http://www.lerc.nasa.gov/WWW/cdtb

Controls and Dynamics Technology Branch

Scope of Work

Propulsion Controls



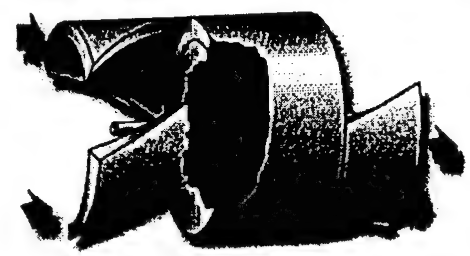
Active Combustion Control
- Emission Minimization
- Control of Thermo-acoustic Disturbances

Inlet Distortion Accommodation
- Online Fan / Compressor Stability Margin Management
- Active Inlet Control

Active Stall Control
- High Bandwidth Actuation & Control Logic
- Stall Precursor Identification

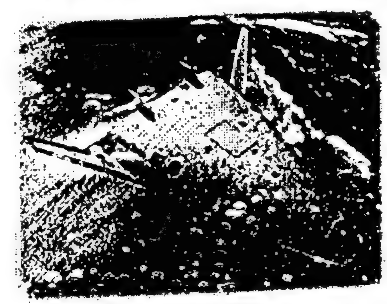
Advanced Control Logic
- Robust Multivariable Control Logic
- Fault Diagnostics & Accommodation

Dynamic Modeling



- Dynamic Modeling of Advanced Concepts
- Controls / CFD Interdisciplinary Research

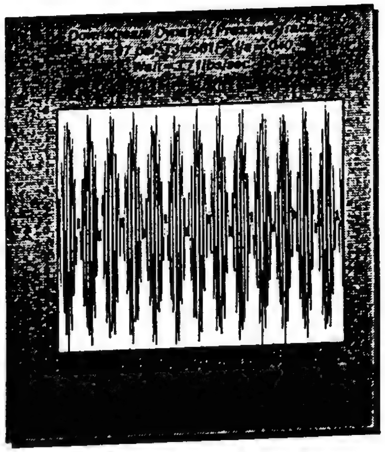
Health Management

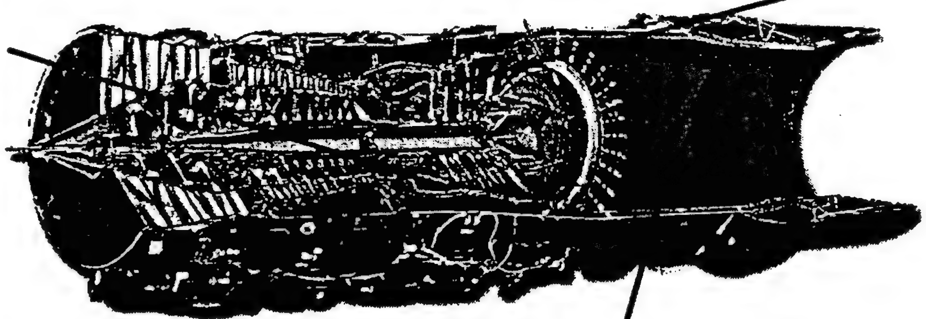


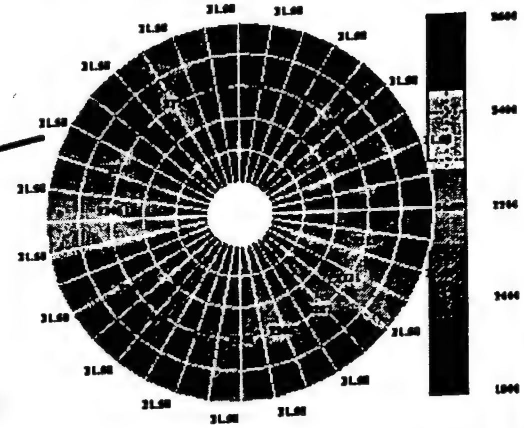
- Sensor Validation
- Post Test Diagnostics

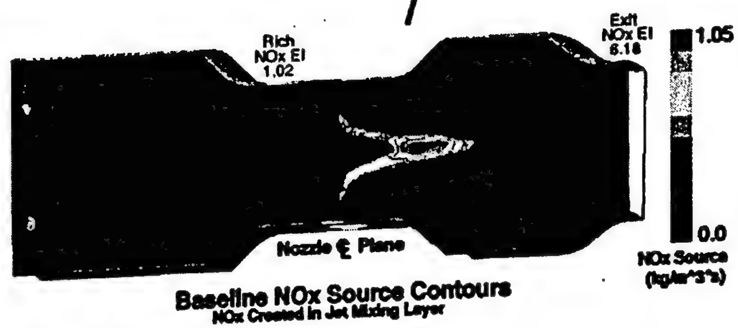
e.jmond wong 9704C3

Active Combustion Controls









Combustion Instability Control

objective: actively suppress thermo-acoustic driven pressure oscillations

participants: P&W, UTRC, NASA (5530, 5830)

Emission Minimizing Control

objective: actively reduce NOx production

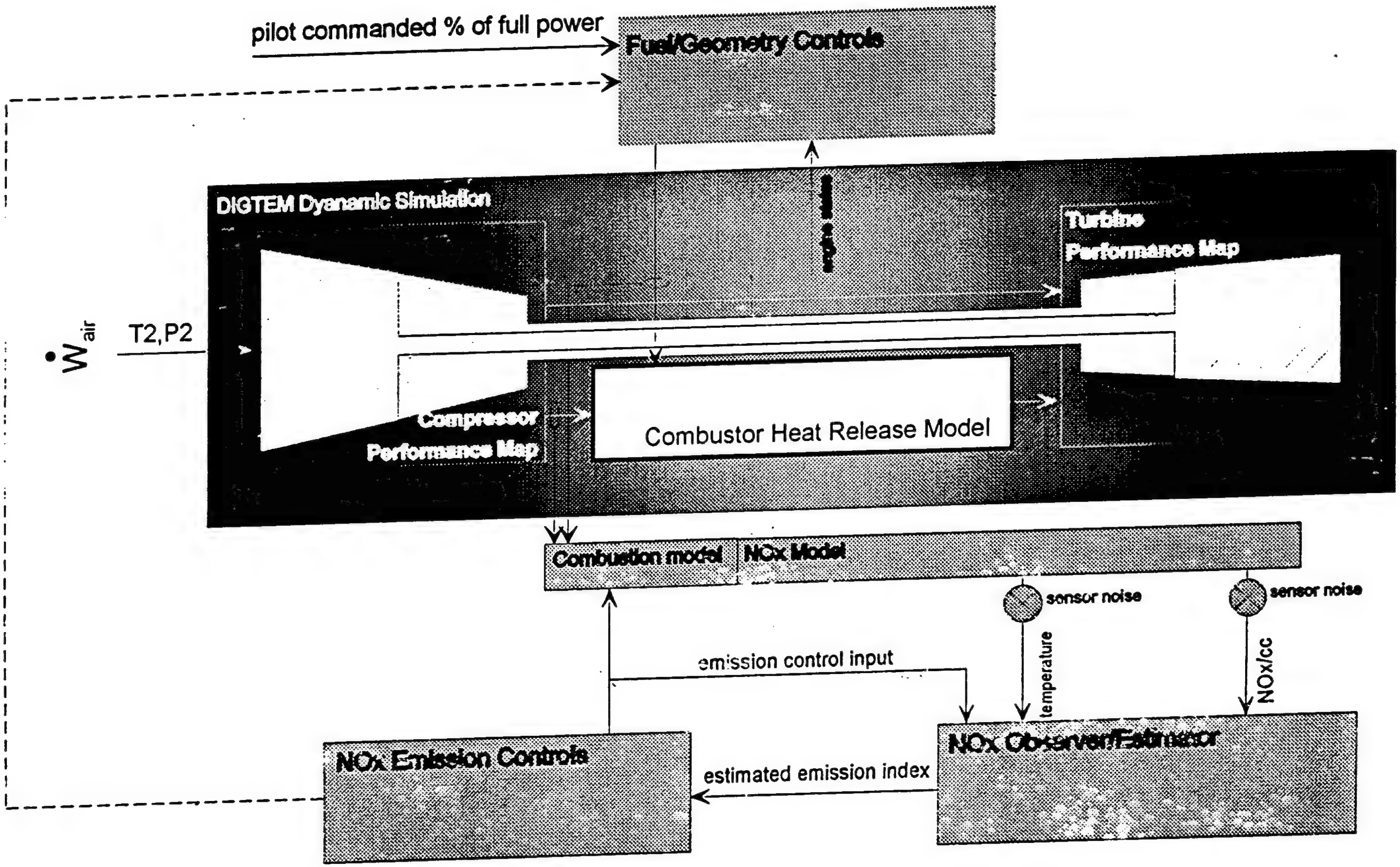
participants: HSR, P&W, NASA (5530, 5520)

Pattern Factor Control

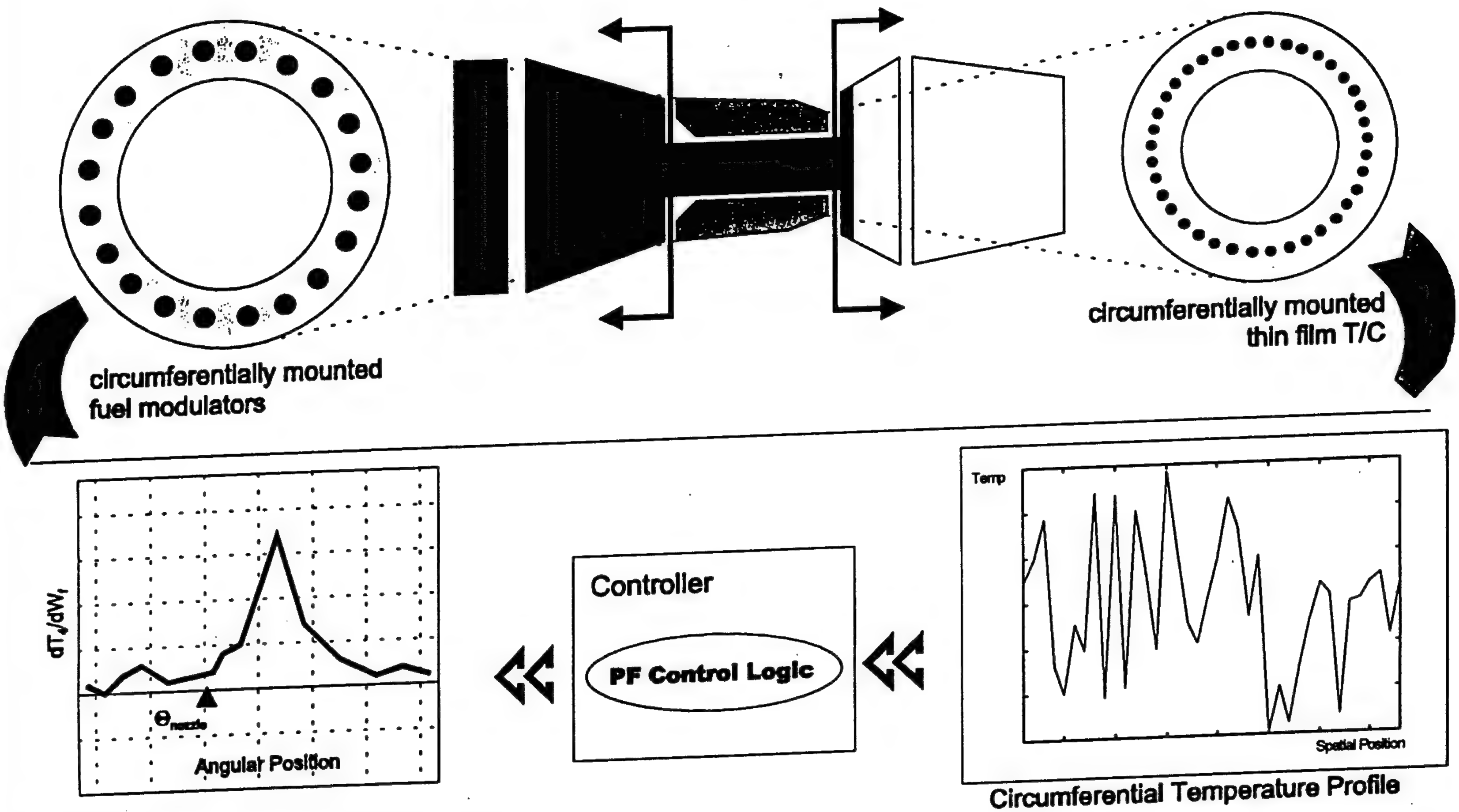
objective: actively reduce combustor patternfactor

participants: AST, Allied Signal, NASA (5530, 5510)

Emission Minimizing Combustor Control Dynamic Simulation
Block Diagram



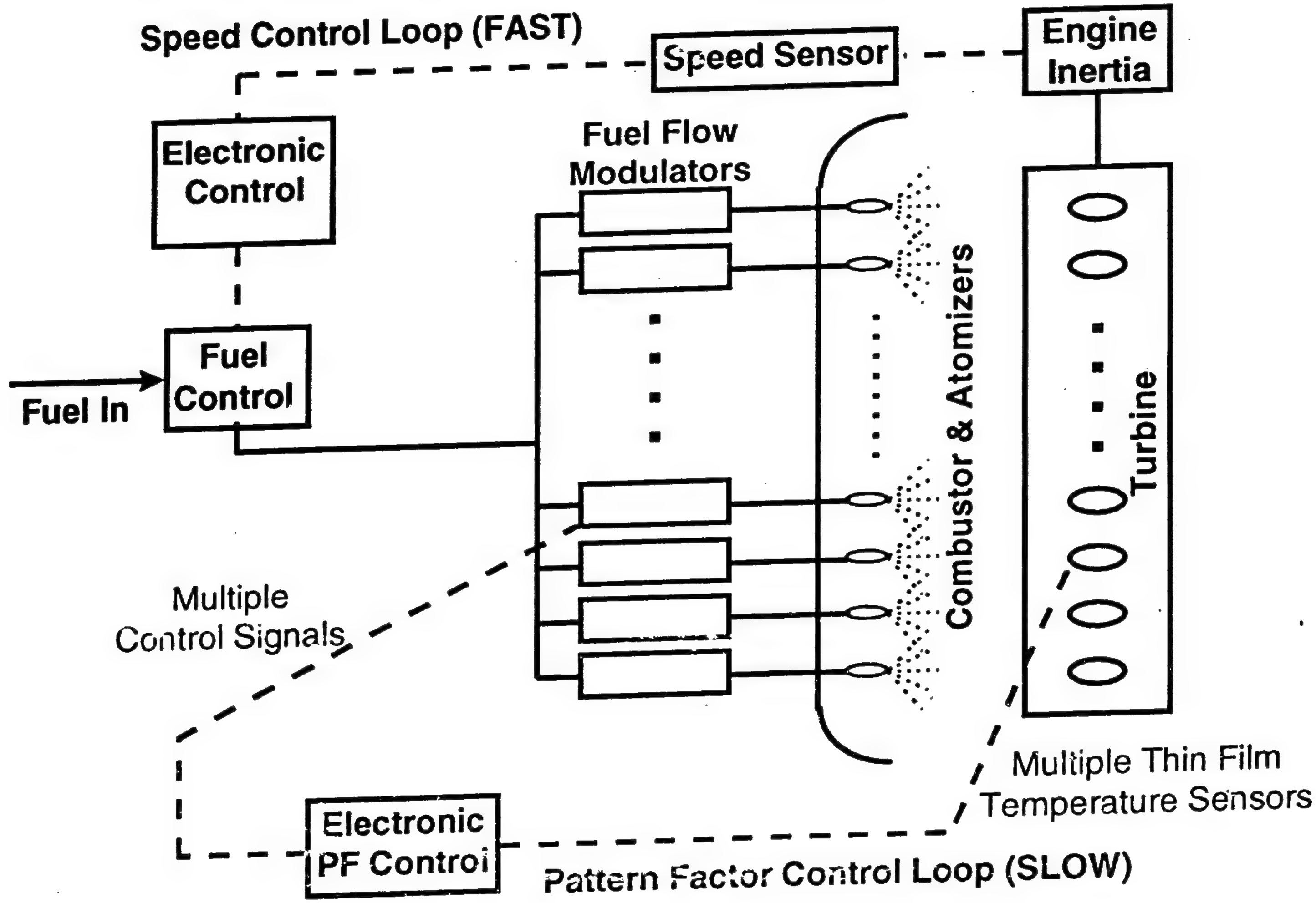
Basic Control Strategy is to use Measured Temperature States in a Closed Loop Configuration



Nozzle Influence Characteristic ($dT/d\Delta W_f$)

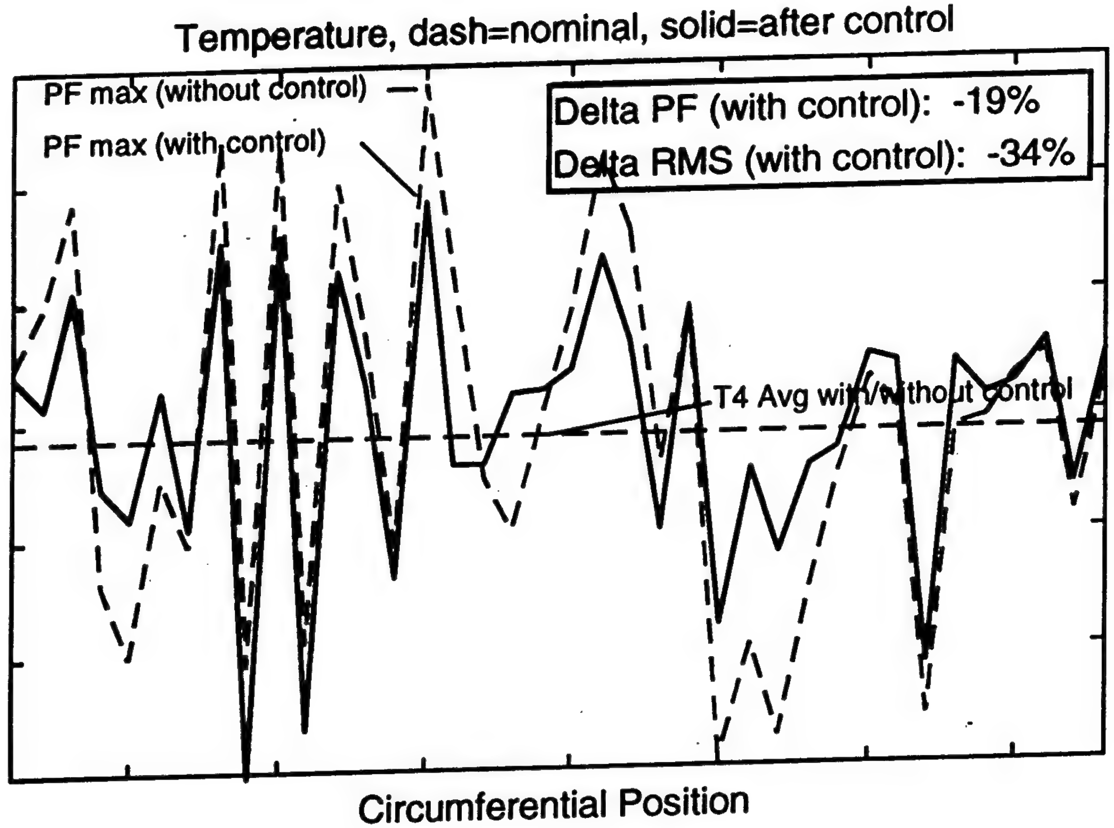
Circumferential Temperature Profile

PF Control Must Work in Parallel with Standard Combustor (Fuel) Control



PF Schematic Diagram

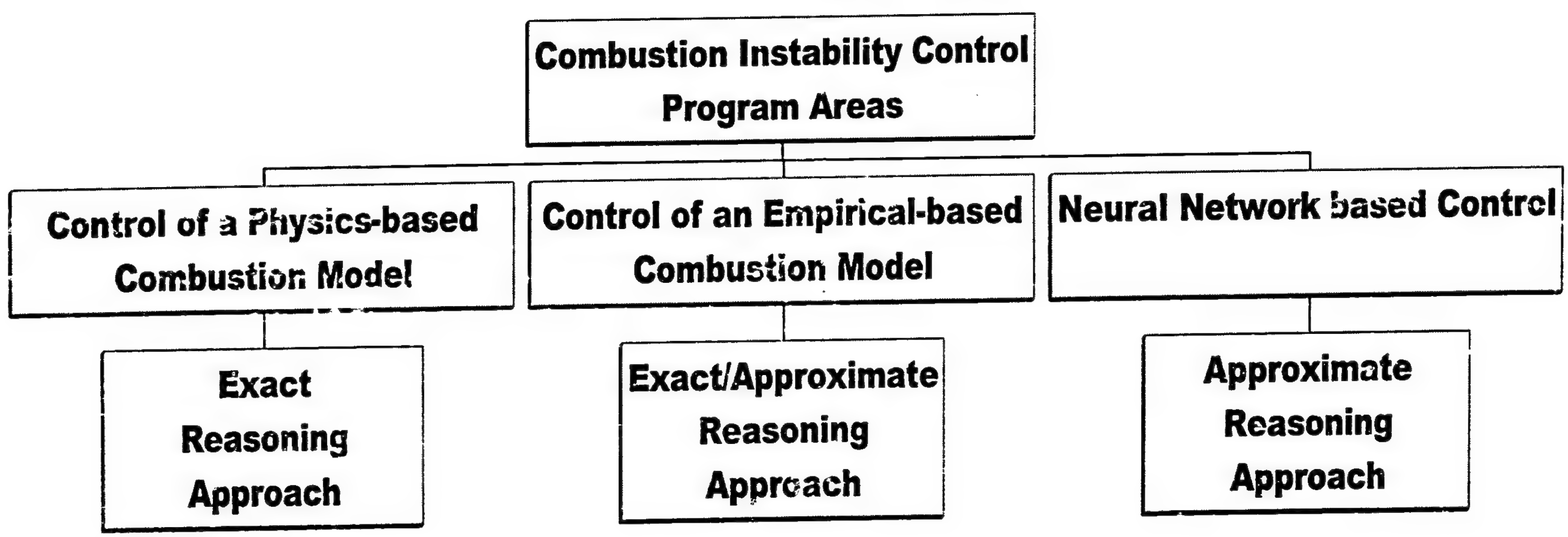
Results of Spatial Averaging Control



Temperature Profile (Simulation Output)

Combustion Instability Control

- Lack of accurate combustion models makes the Exact Reasoning approach a higher risk, long term payoff solution
- Approximate Reasoning approaches would be a lower risk and more near term payoff solution
- 3 Programs areas were constructed to cover the Controls approach spectrum



Physics-based Combustion Model Control

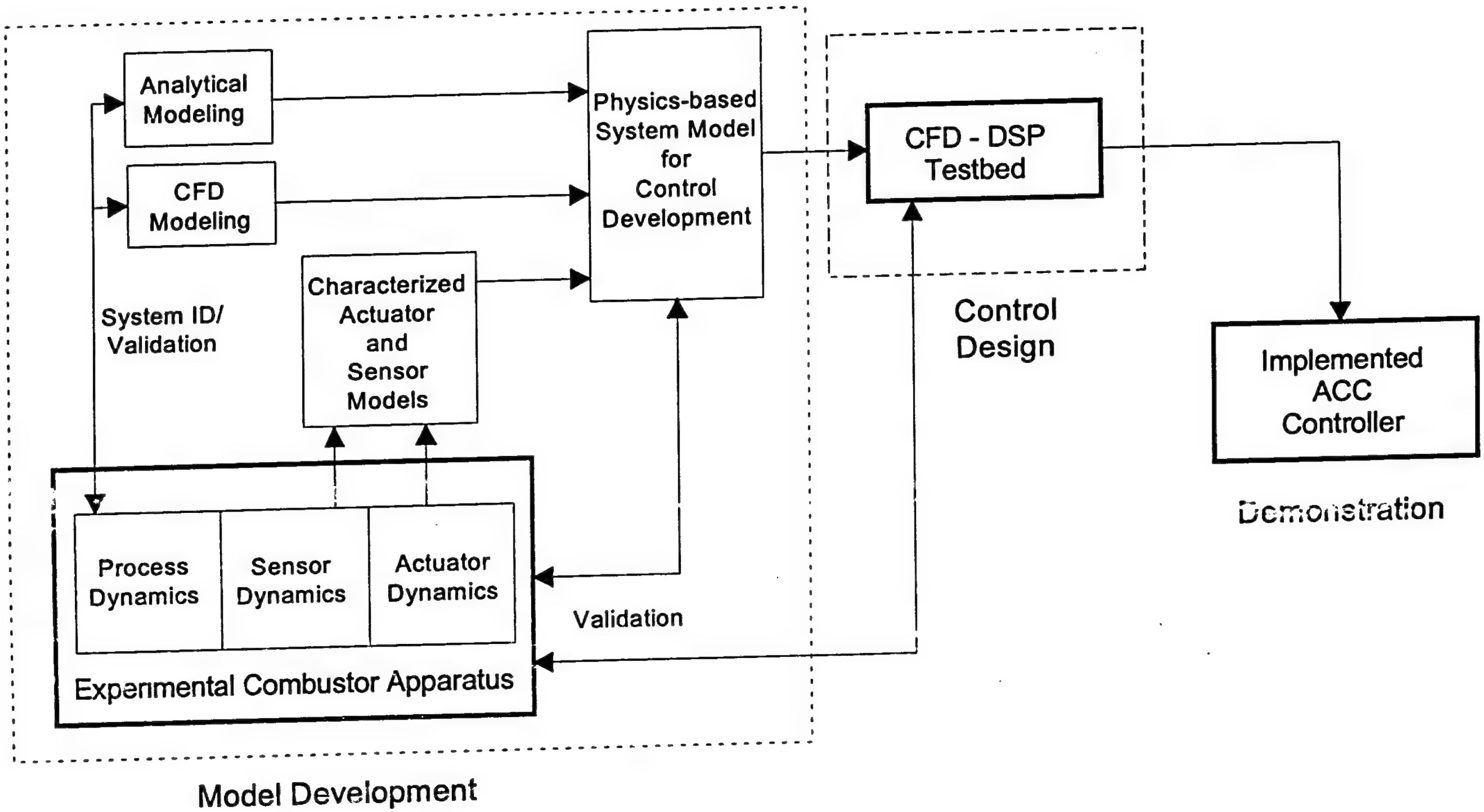
Primary Focus: To develop an exact reasoning closed-loop control solution for ACC through a combined application of Control System Theory, Experimentation, and fully-coupled, nonlinear CFD modeling which incorporates both process and system dynamics.

Main Objectives

- develop experimentally-corroborated analytical and numerical system models for closed-loop control design
- develop a CFD-DSP testbed for real-time system identification, closed-loop control evaluation, and control-plant interaction analysis
- experimentally demonstrate closed-loop ACC

Physics-based Combustion Model Control

Basic Developmental Steps



Empirical-based Combustion Model Control

Objective: Develop and demonstrate active control solutions for the combustion instabilities anticipated in advanced aero-engines

Approach: Two Phase approach encompassing improved understanding and modeling of physically observed phenomenon and demonstration in relevant test environment

Phase I:

- Investigate, identify and document a "model problem" engine combustion instability relevant to advanced gas turbine engines
- Design and build an engine-scale single-nozzle test rig to replicate and demonstrate the baseline instability
- Perform combustion tests to charaterize the combustion instability and determine the sensitivities to operating conditions
- Develop a detailed program plan for Phase II to research, develop and demonstrate active control solutions for combustion instabililities

NASA LET63A Single-Nozzle Acoustic Rig

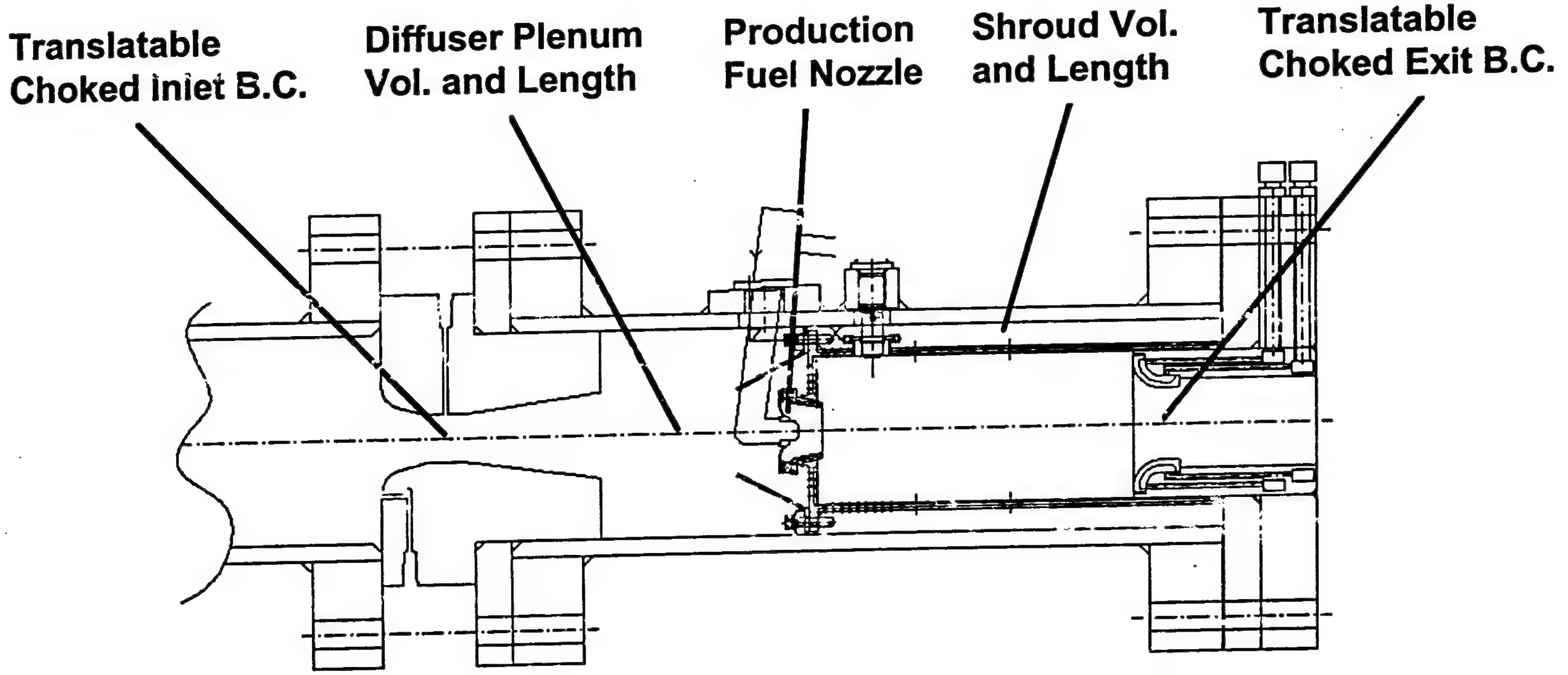
A Single-Nozzle Test Rig with Acoustic Flexibility Is Being Built

Objective: Demonstrate ability to produce combustion dynamics in a SNR rig that are similar (freq., amp.) to a measured engine case

Phase 2 will look at active control of longitudinal modes

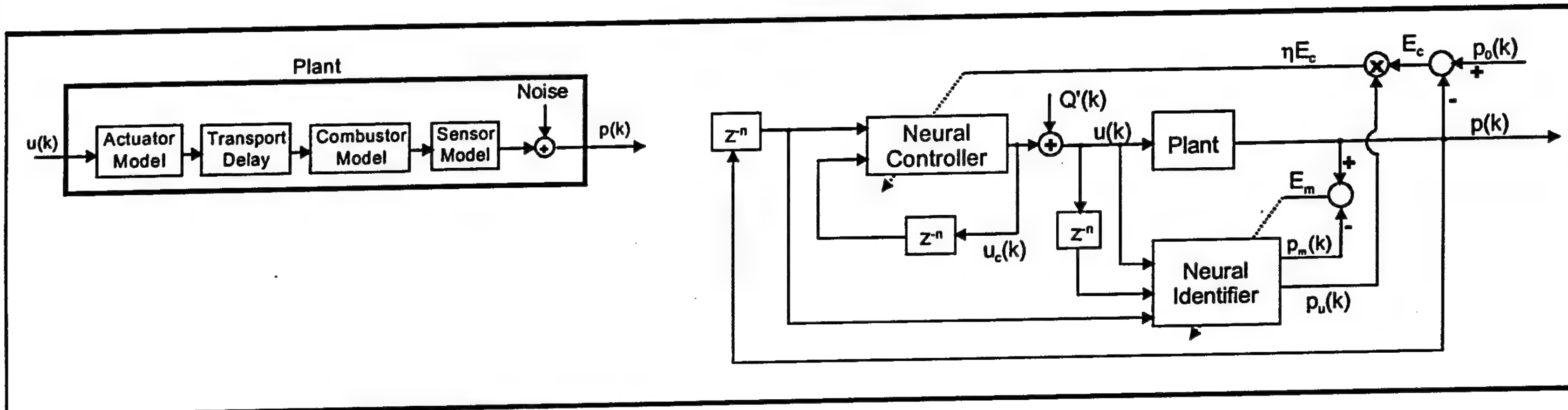
Approach: Design test rig with the same lengths and volumes as engine combustor

Include flexibility to change inlet and exit b.c.'s to allow for acoustic tuning



Neural Network-based ACC

- Combustion instability is a highly nonlinear process
- Neural Networks have good nonlinear control abilities; their parallel architecture facilitates real-time control
- Given these two facts, it is logical to devise a neural network-based scheme for ACC



Neural Network-based ACC Scheme (NACC)

NACC Scheme Comprised of 3 Main Componenets

1.) 1-D Combustion Model

2.) Diagonal Recurrent Neural Network (DRNN) Neural Identifier

3.) DRNN Neural Controller

Neural Network-based Control

3 Stages of Development

Stage 1

- Implementation of 1-D Navier-Stokes based combustion model
- Design and training of neural controller
- Closed-loop control evaluations
- Iterate on controller design and training (if required)

Stage 2

Part 1

- Perform characterization tests on a flame tube combustor test rig
- Modify 1-D combustion model used in stage 1 to exhibit characterized behavior

Part 2

- Perform closed-loop control evaluations using modified model and the controller from stage 1.
- Iterate on controller design and training (if required)

Stage 3

- Demonstrate closed-loop control on the flame tube combustor test rig

NACC Results

Plant Operating Condition

$T_i = 1000\ ^{o}K$ $P_i = 506.6$ kPa

$T_e = 2000\ ^{o}K$ $P_e = 101.3$ kPa

$v_i = 100$ m/s

Air = working fluid

Combustor Length = 1 m

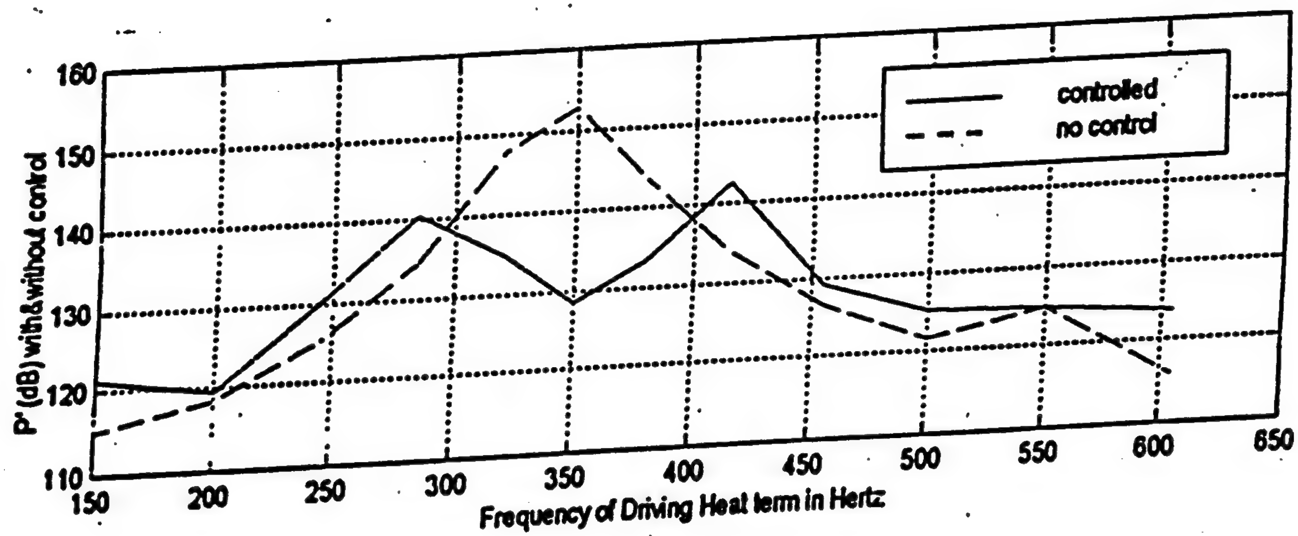
Combustor Cell Width = 0.02 m

Flame Front Location = 0.5 m

Pressure Sensor Location = 0.45 m

Primary Resonant Frequency = 350 Hz

Primary Resonant Frequency Mode Shape = Nominal Half Wavelength



Combustion Instability Modeling

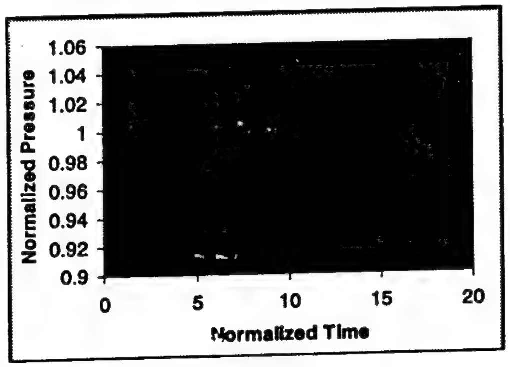
Approach:
•First principles modeling using Q-1-D Euler Equations with Chemical Kinetics and Diffusion (limited to pre-mixed flows).

Features:
•Variable geometry.
•Variable boundary conditions.
•Secondary cooling air.
•Simple & Fast.

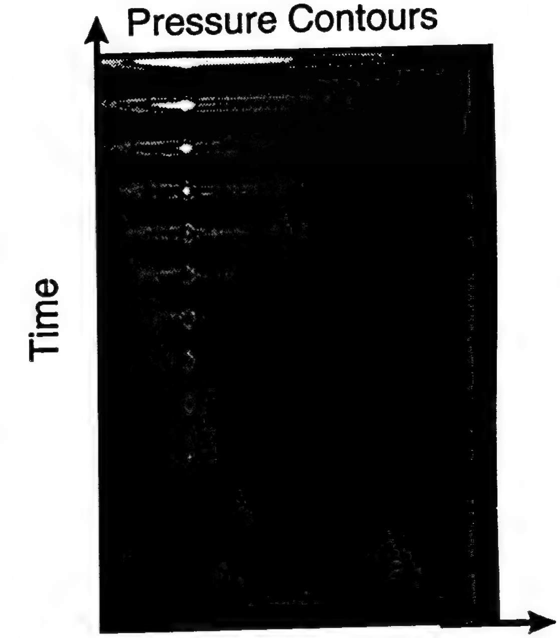
Progress:
•Successful simulation of thermo-acoustic oscillations in a flametube.
•Validated simulation of LeRC LPP rig instability.

Future Work:
•Non-premixed capability.
•Model unsteady effects of flameholder & injector.

Pressure at Tube Center



Flametube simulation showing development of self-induced thermo-acoustic oscillations



Participants:
D. Paxson, LeRC
D. Quinn, U. of Akron

Goals and Technologies for Tomorrow's Gas Turbines
June 15 - 16, 1998

SESSION V: OPEN FORUM

FUTURE TRENDS IN GAS TURBINE SYSTEMS

Moderator:
Dr. Geoffrey J. Sturgess
Innovative Scientific Solutions, Inc.

GEORGIA TECH WORKSHOP

MAJOR GAS TURBINE ENGINE CHALLENGES

- Very high altitude operation at low flight Mach Nos.
- Low exhaust NOx without premixing
- DLN for liquid and gaseous fuels in advanced engines
- Reduced cost and weight
- Accommodation of very high by-pass ratios
- Packaging low-power units with high efficiencies

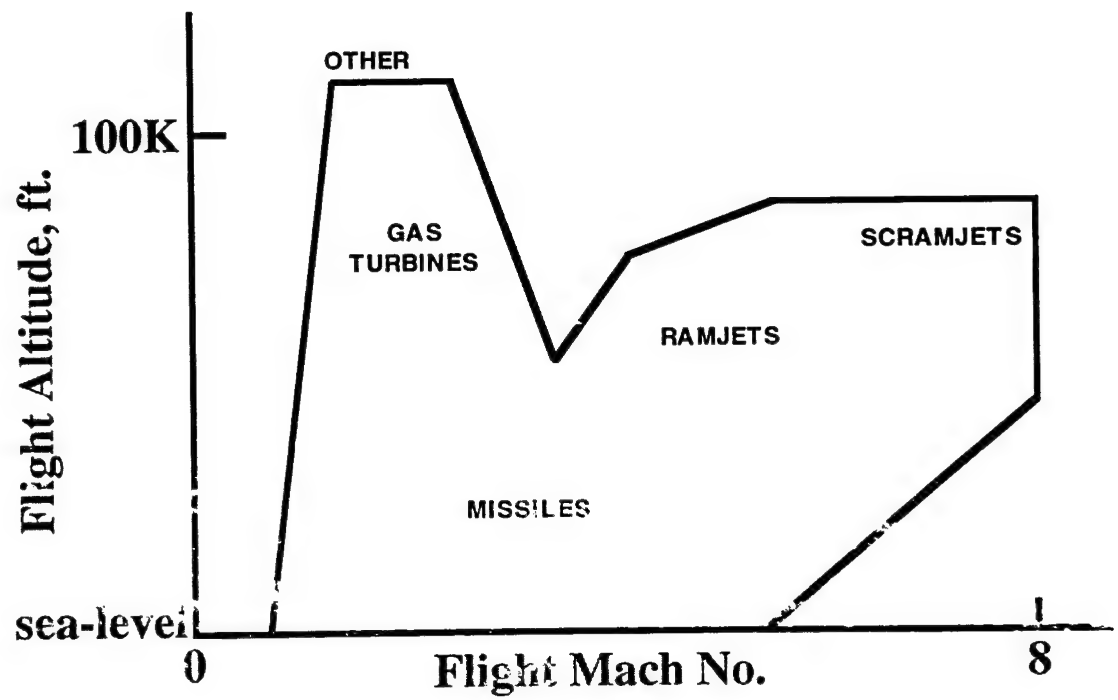
Concentrating on combustion aspects

ROLE OF COMBUSTION

- Combustion is a major player for:
  - high altitude operations
  - low NOx
- Combustion can play a part in:
  - reduced weight and cost
- Combustion is not a driver in:
  - high bypass ratio
  - low-power units (except ultra-small)

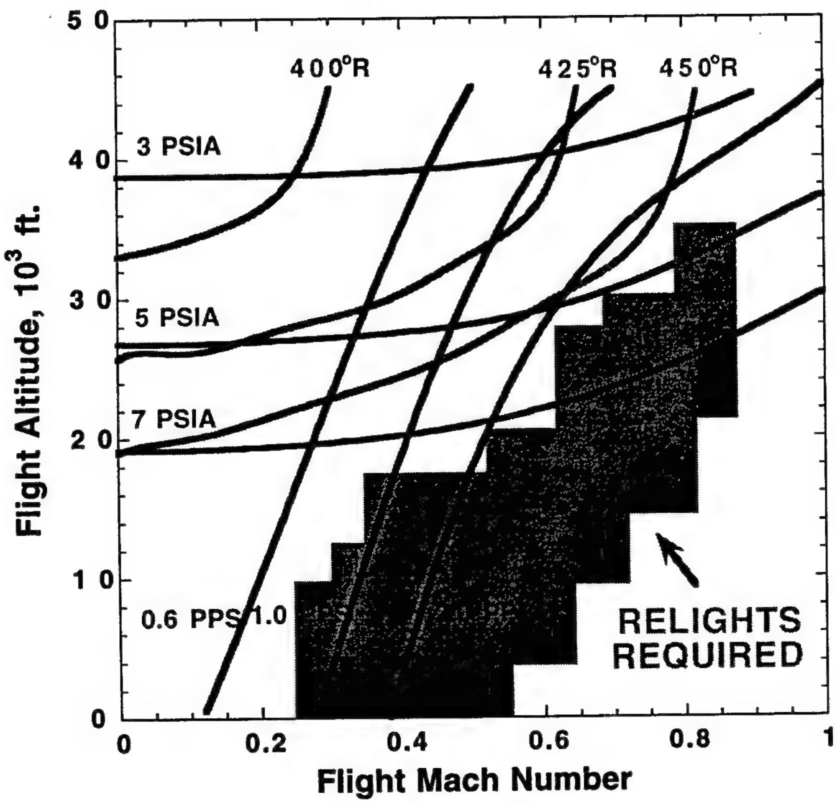
GAS TURBINES IN UAV's

- Nitch for gas turbines



Altitudes considerably beyond current general experience

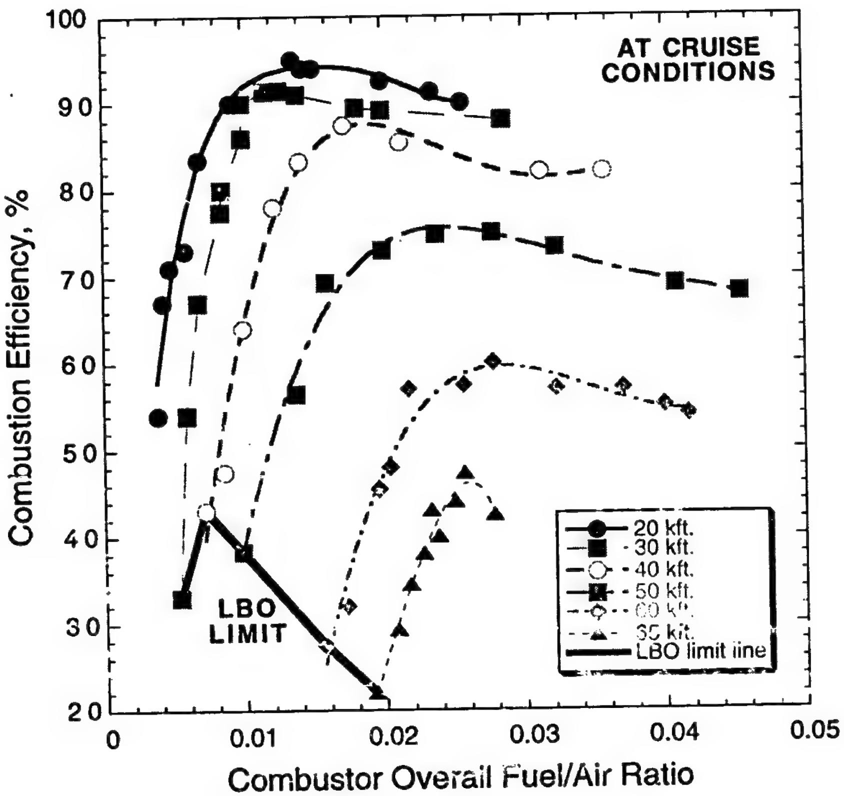
WINDMILLING RELIGHT CONDITIONS



- Conditions for ignition can be extreme
- Liquid fuel atomization can be poor
- Heat losses from spark kernel can be high
- Air velocities can be high

Descent from altitude frequently necessary

EFFECT OF ALTITUDE ON EFFICIENCY



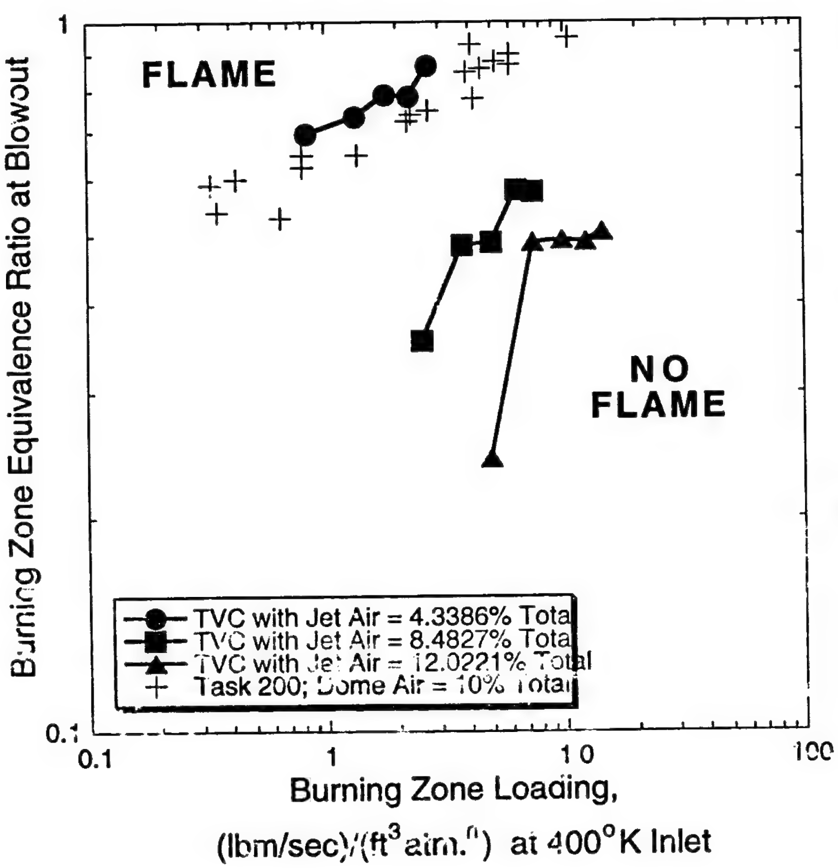
- Operating line constrained between LBO and peak efficiency
- Constraints "close-in" with increasing altitude
- Station keeping limited by poor fuel burn

Operation above 60,000 ft. is difficult

VERY HIGH ALTITUDE OPERATION

ISSUES	APPROACHES	DRAWBACKS
LBO stability	Trapped vortex	Staged system, durability
Dynamics at LBO	ACC	Reliability, cost control issues
Combustion efficiency	Catalytic enhancement	Durability
	Ionization of fuel/O_2	Energy cost
	Reduced/external cooling	Durability
	Rate-enhancing fuel additives	Effectiveness/cost unknown
Ignition	Oxygen injection	Ancilliary system
	Pre-chamber	Durability
	"Smart" spark	None known
	Ionization of fuel/O_2	Energy cost

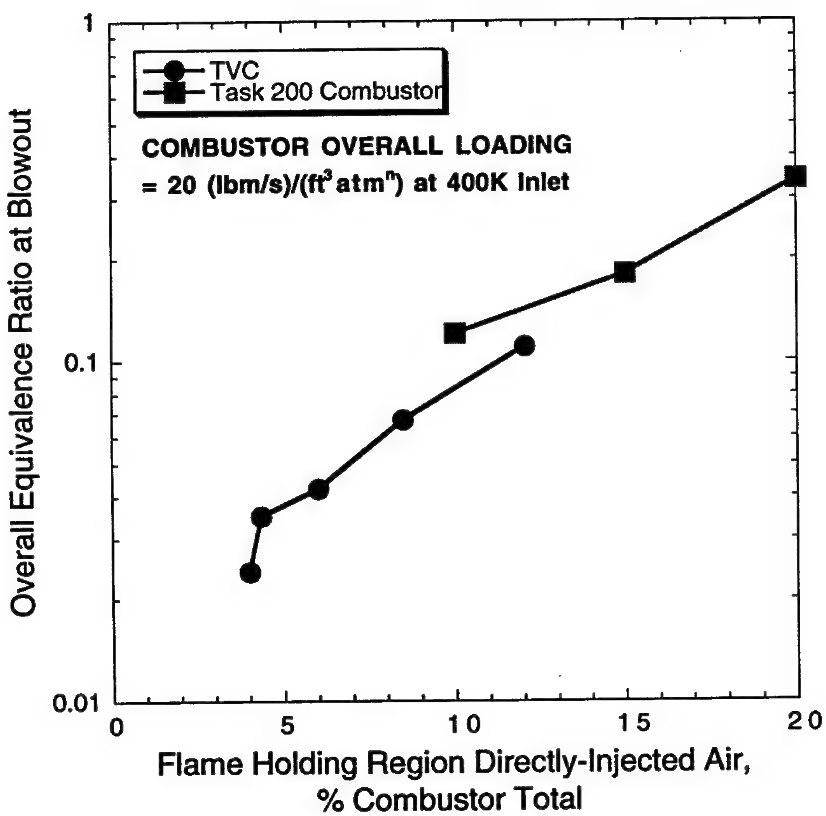
TVC AS A PILOT COMBUSTOR



- Increasing cavity loading at fixed jet air (% total) reduces stability
- Increasing jet air (% total) at fixed cavity loading increases stability
- Compared to swirl-stabilization at same "direct air", TVC has improved stability

TVC promising as "Pilot"

COMPARISON WITH SWIRL-STABILIZED COMBUSTION



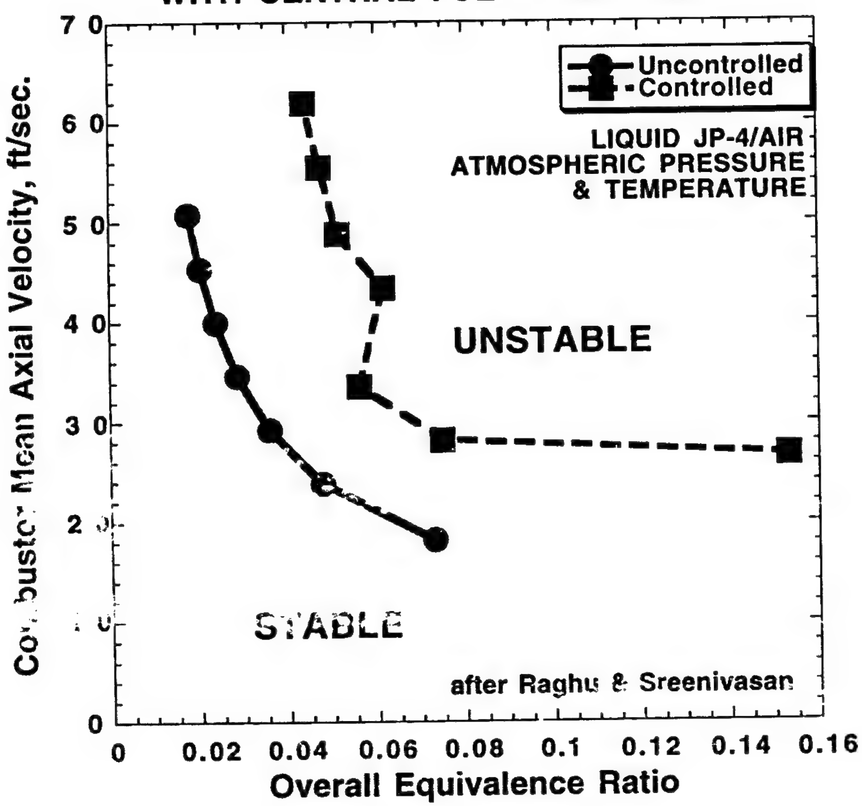
- **For swirl-stabilized combustion,**
  "Directly-injected" air = Dome air
- **Sensitivity of TVC virtually same as swirl-stabilized combustor**

TVC has no advantage as a stand-alone

GEORGIA TECH WORKSHOP

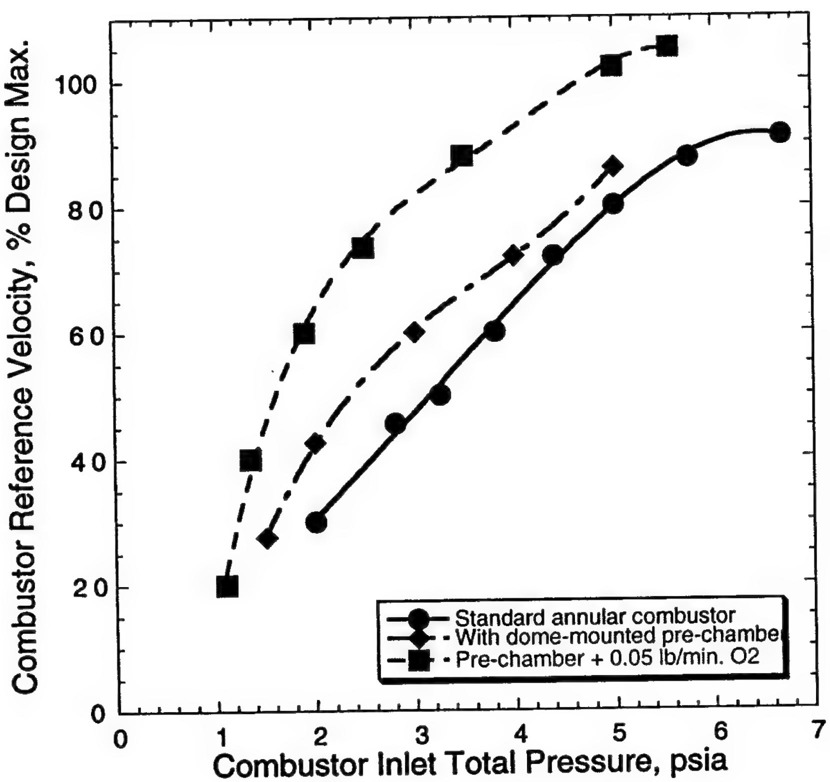
COMBUSTION STABILITY

ROQUEMORE et al.
AXISYMMETRIC BLUFF-BODY COMBUSTOR
WITH CENTRAL FUEL INJECTION



- Blow-out at extremes of fuel/air ratio can be set by instabilities
- Active control can restore blowout limits close to flammability limits
- Active control might also be able to enhance LBO by inducing local fuel/air unmixedness

IGNITION BY BRUTE FORCE



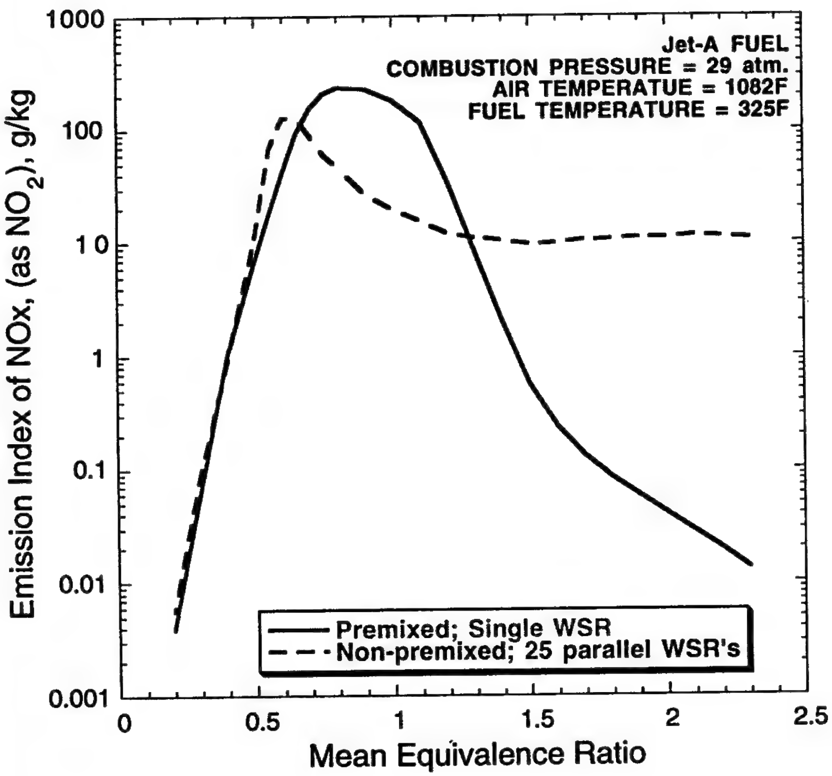
- Retro-fit not possible
- Costly solution

A little oxygen addition goes a long way

LOW NOx WITHOUT PRE-MIXING

ISSUES	APPROACHES	DRAWBACKS
Improved fuel/air mixing	Multi-point fuel injection	Multi-staging needed Coking, Size and cost issues
	Synthetic jets	Reliability, control, cost issues
Near-elimination of wall cooling	New materials conventional use/ new materials unconventional use	Can they deliver? Radical layout mods. effects on profile factor?
Dynamic instabilities role	Active combustion control	Reliability, control issues, cost, noise
Staging without fuel-burn penalties	Smart controls	Multi-staging, engine response?
A priori emissions calculations	Reduced chemical reaction mechanisms	Detailed flow and chemistry necessary

FUEL/AIR MIXING AND NOx



- **With current mixing and designs, not much hope!**
- **Staging (either RQL or lean/lean) gives better prospects**
- **Improvements in mixing necessary**

Better presentation of liquid fuel to air

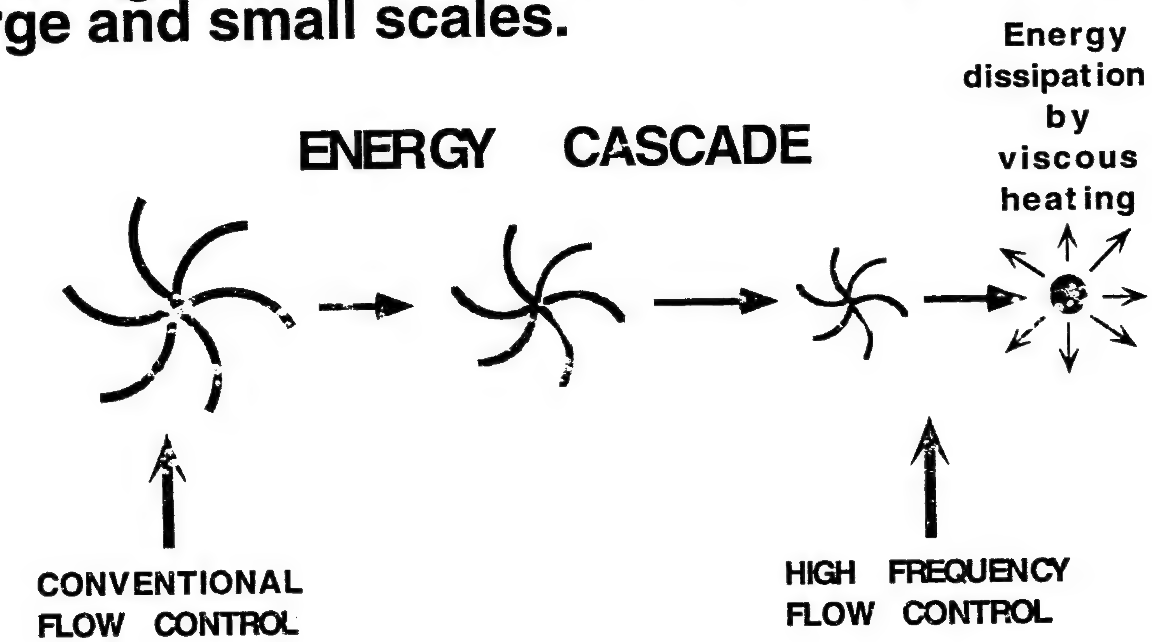
GEORGIA TECH WORKSHOP

ISSI

IMPROVED MIXING

- Conventional mixing follows "turbulence energy cascade" from large eddies down to small eddies (Kolmogorov scales). Mixing devices usually manipulate large-scale vortices, which:
  - directly "stirs" fuel and air, and,
  - is only weakly coupled to Kolmogorov scales.

- Active mixing control can simultaneously manipulate directly, both large and small scales.

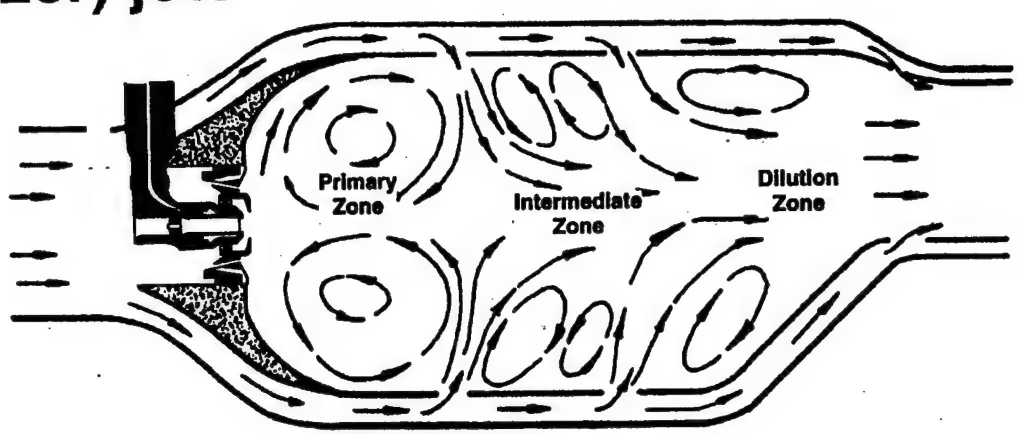


SYNTHETIC JETS

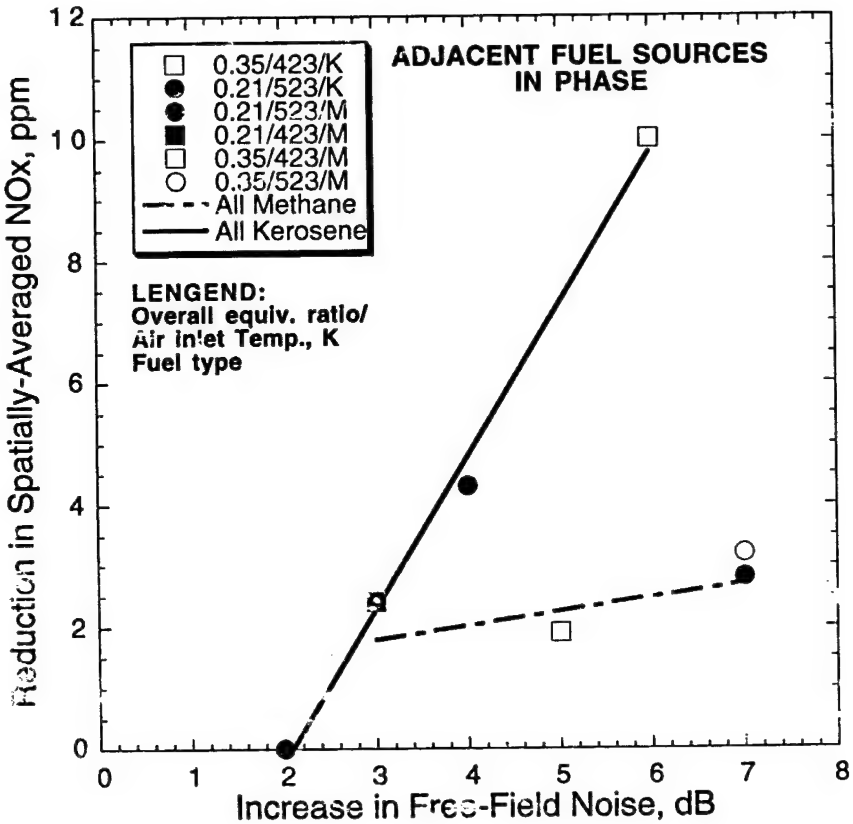
- By means of active control, a jet of fluid entering the combustorcan have its:
  - initial angle of trajectory
  - cross-sectional shape

  changed as desired. Its cross-sectional shape can be spun about the jet axis. The jet can be pulsed along its trajectory.

- The active control can be applied to either air or fuel/air (airblast atomizer) jets



LOW NOx - ROLE OF DYNAMIC INSTABILITIES



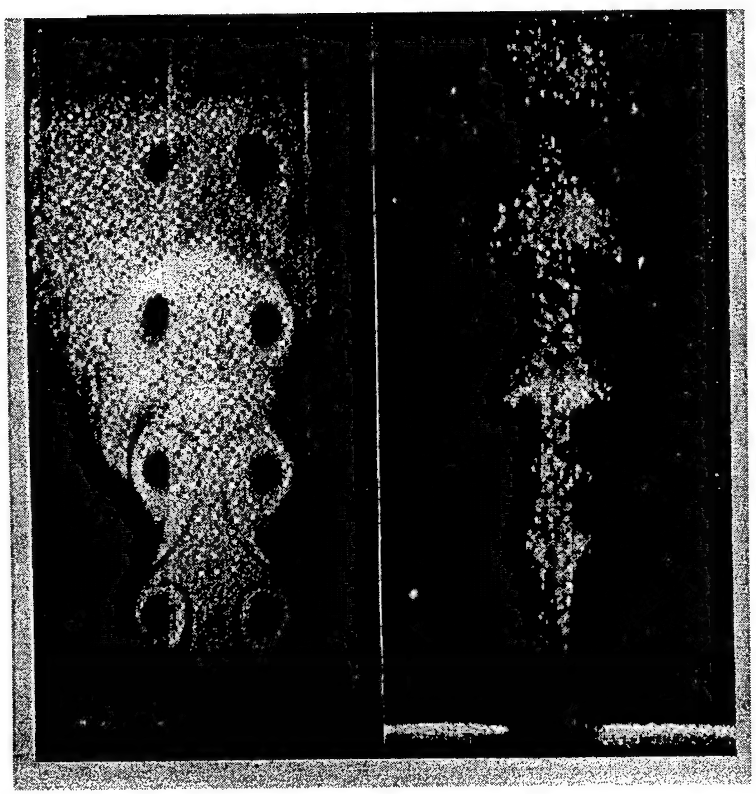
- Can reduce NOx, but with increase in noise

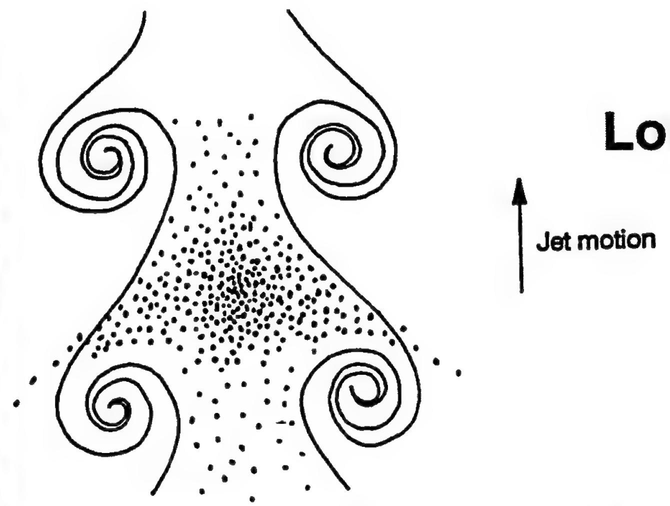
(Poppe, Sivasegarem & Whitelaw, Combustion & Flame, 113:13-26, 1998)

Demonstration, but not understanding

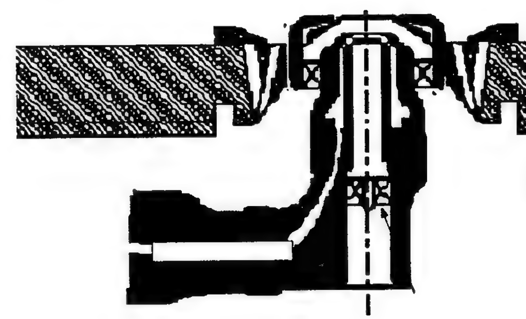
LIQUID FUEL DYNAMICS

Flow fluctuations can adversely influence temporal and spatial fuel/air mixedness, with potential negative effects on NOx emissions





after
Longmire & Eaton



Typical Airblast Atomizer in Combustor Dome

REDUCED WEIGHT AND COST

ISSUES	APPROACHES	DRAWBACKS
Elimination of CEGV's	Swirl combustor (30-35^{o})	Stratification, Durability, Close coupling of compressor
Elimination or simplification of TIGV's	Swirl combustor	Increase in swirl Close coupling of turbine Requires new turbine design philosophy

LOW AND ULTRA-LOW POWER ENGINES

- Is scale-down of conventional layouts best for component efficiencies?
- Novel layouts might require novel combustion systems
- Very small size brings on Reynolds No. problems for combustion

SUMMARY

- Combustion remains a significant contributor to meeting advanced gas turbine goals
- There are still many basic science issues and needed technology developments in combustion
- Combustion dynamic behavior is of growing importance
- The elegant simplicity of current combustion systems could disappear as the engine operating envelope expands. Be prepared to "step out of the box!"

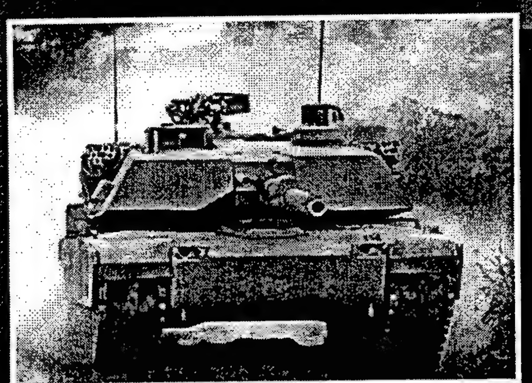
Research Needs for Future Gas Turbines -a U.S. Army Perspective

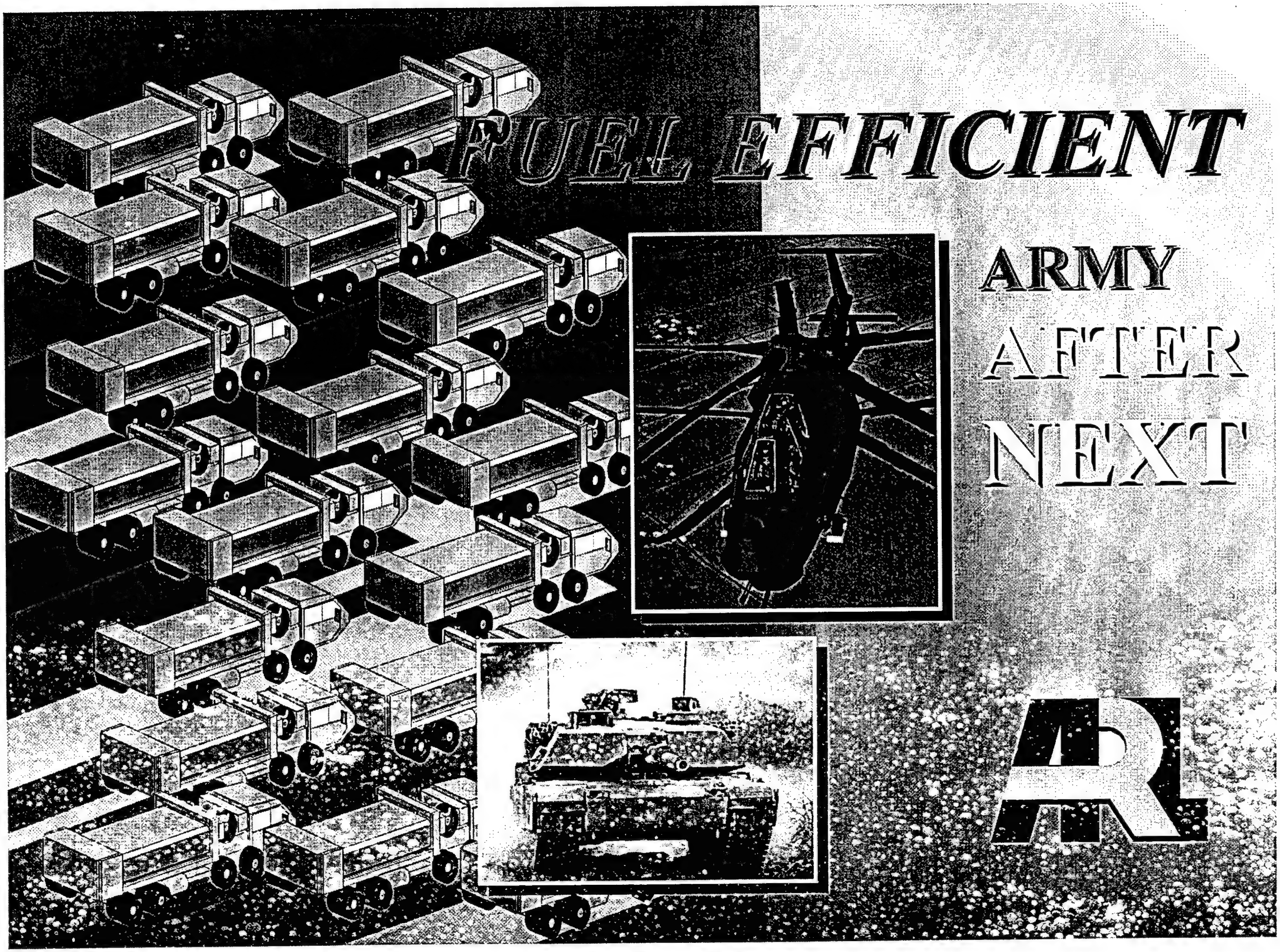
by Dr. Edward J. Mularz

Vehicle Technology Center

Army Research Laboratory

June 16, 1998



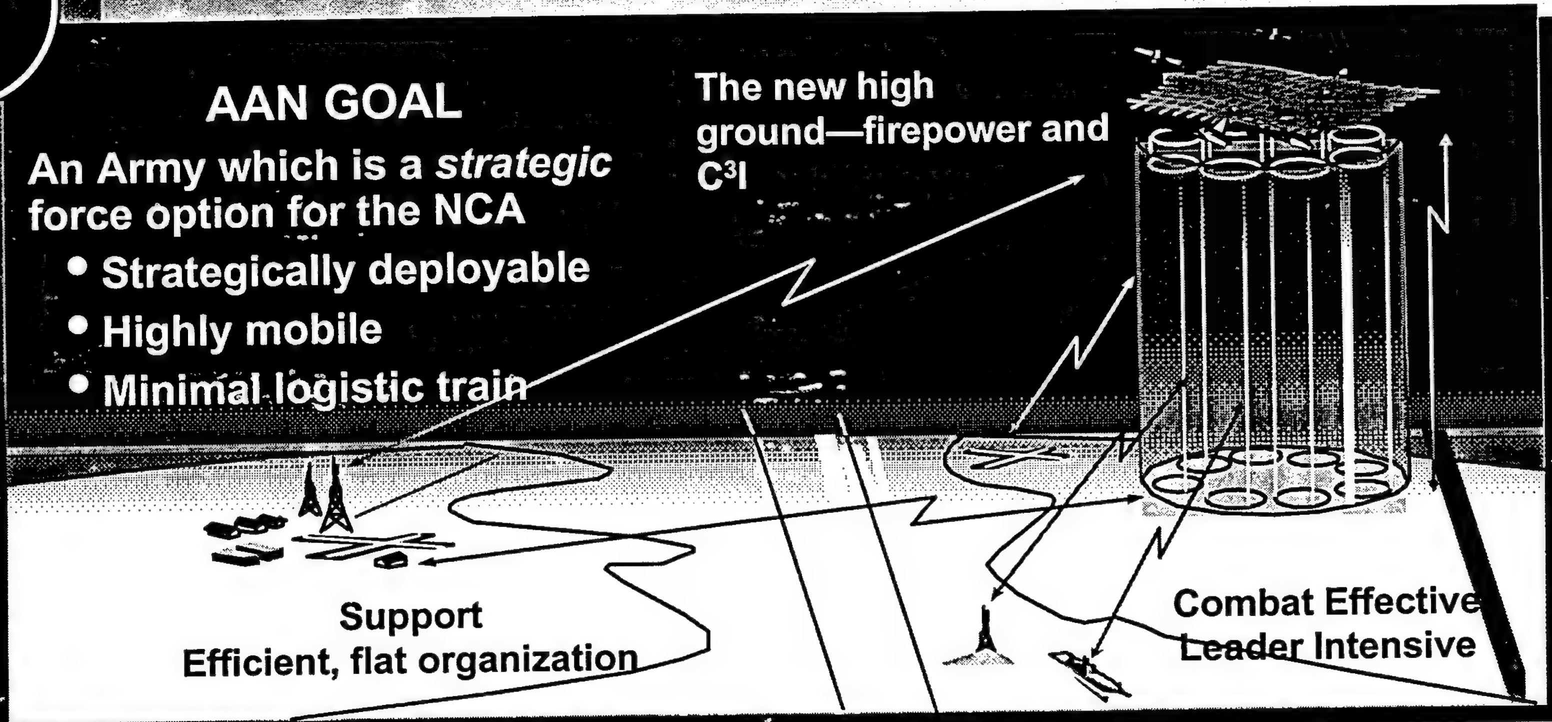

FUEL EFFICIENT
ARMY
AFTER
NEXT

ARMY AFTER NEXT

OBJECTIVES

- 2020-2025 Time Period Technology Insertion
- Information dominance
- Mobility exploitation
- Fuel Efficient Initiative:
  - Eliminate 75% of fossil fuels from the battlefield
  -

OPERATIONAL CHARACTERISTICS of AAN (20XX)



- Battle Force Units with combined air and ground capabilities at lowest levels
- All operating systems resident within battle force
- "Reach-back" for combat functions (Fires, C^2, Logistics)

- Independent operations for 2 to 14 days without resupply / refuel
- Self-protection through movement, organic weapons, low-observables, and situational awareness
- Engage enemy with information, organic, and inorganic weapons

Fuel efficiency is a critical enabler

BATTLEFIELD LOGISTICS

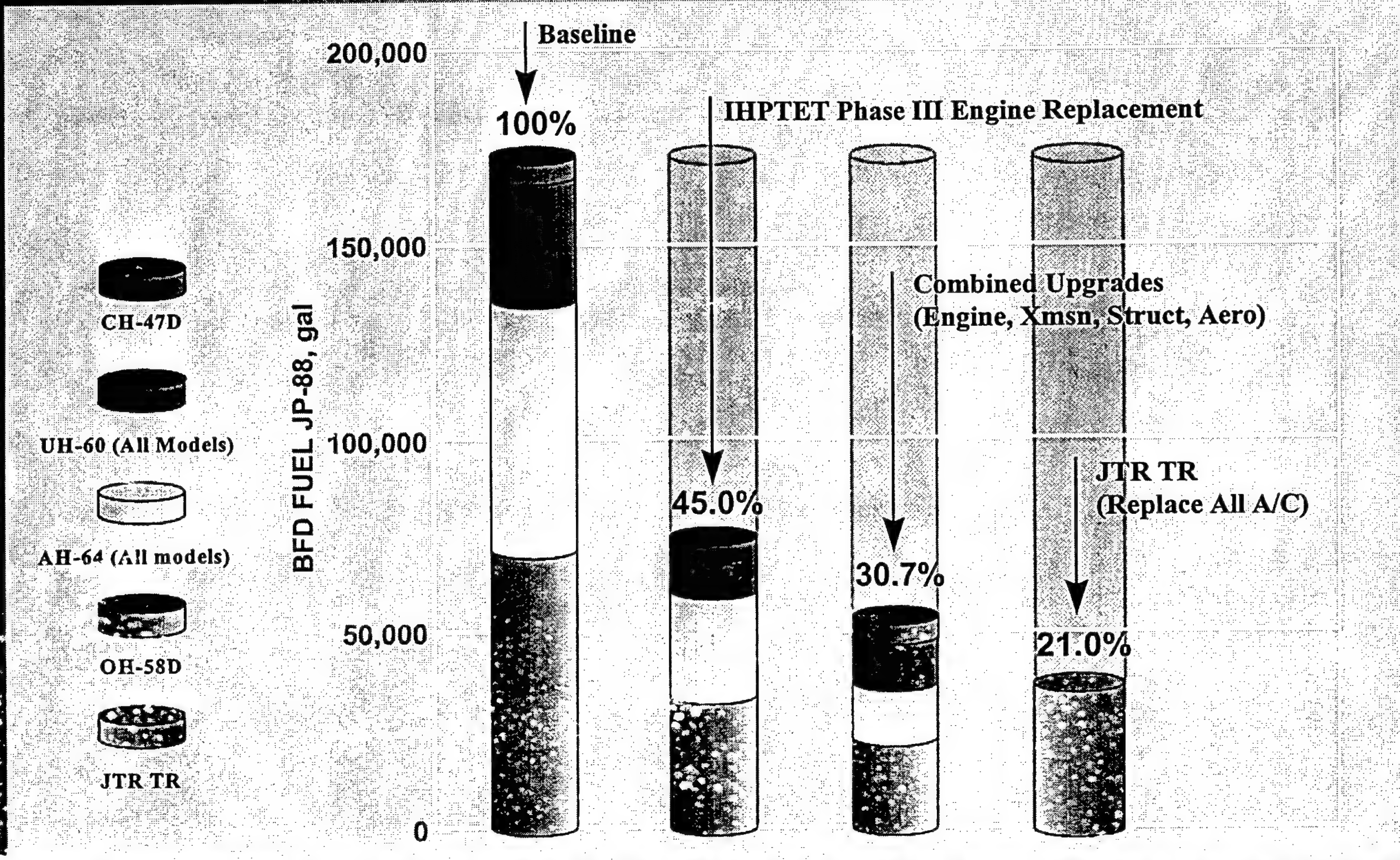
- Fuel comprises 70% of tonnage shipped
  - Armored division consumes approx. 600,000 gal/day
  - Air assault division requires approx. 300,000 gal/day
- Future battlefield scenarios may very likely impose severe fuel availability constraints
  - Global geopolitical environment
  - Short lead time for deployment preparation
  - Fuel requirements may well pose a major obstacle to exercising deployment options

WHITE PAPER

Battlefield Day (BFD) fuel requirements were analyzed for:

- Armored Division
- Air Assault Division
- Mechanized Infantry Division

AIR ASSAULT DIVISION MANEUVER BRIGADE
BFD FUEL CONSUMPTION



Assumptions: Mideast Conditions
Mission Radius, Take-Off GW, and Total Productivity Held Constant for CH-47D, UH-60, AH-64
Total Distance Swept Held Constant for OH-58D

TURBOPROP/TURBOSHAFT GOALS

AP.07.00.ANF TRANSPORT/PATROL/HELICOPTER PROPULSION

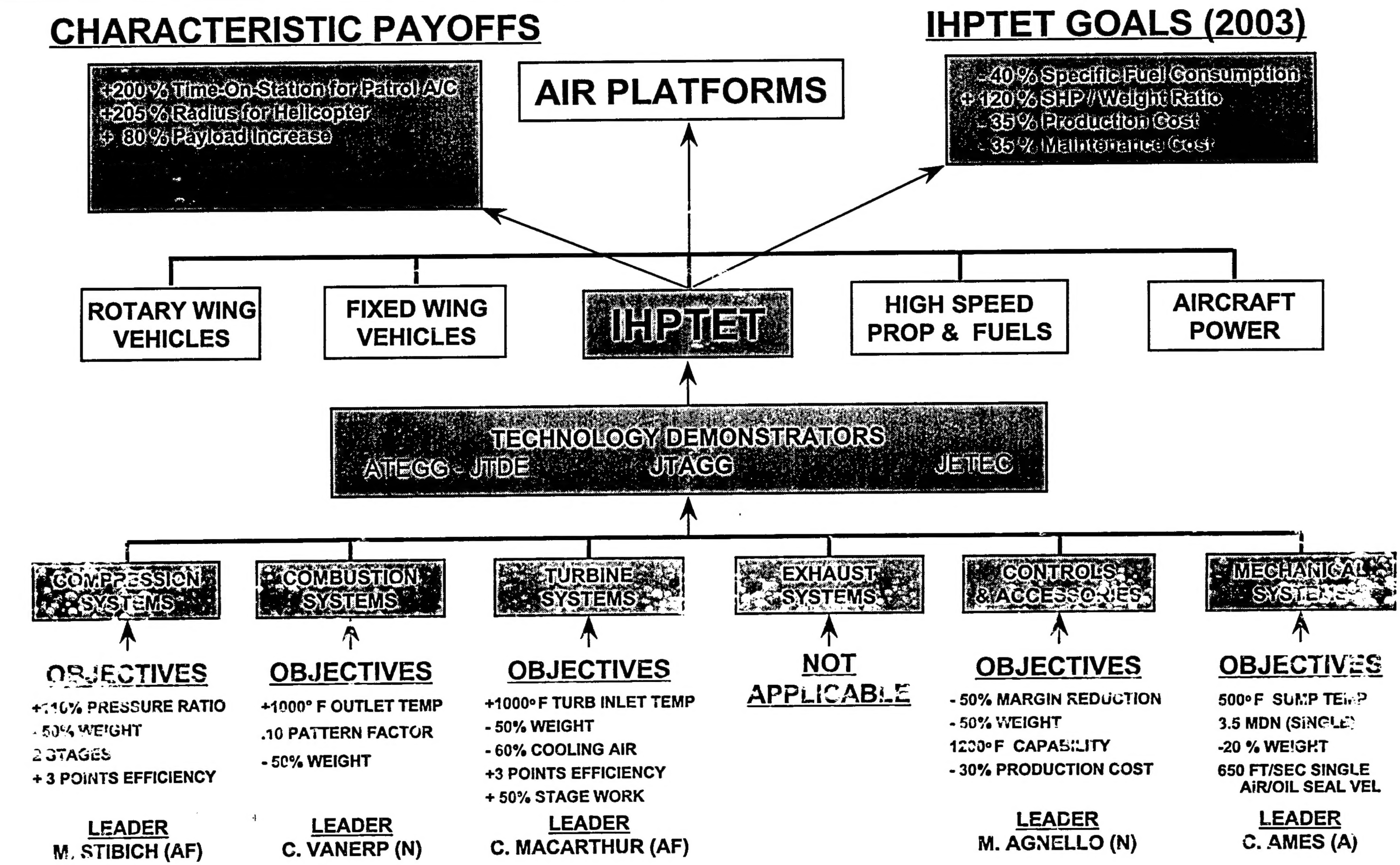
	PHASE I	STATUS	PHASE II	PHASE III
SFC	- 20%	- 22%*	- 30%	- 40%
HORSEPOWER/WEIGHT	+ 40%	+ 63%*	+ 80%	+120%
ACQUISITION AND MAINTENANCE COSTS			- 20%	- 35%

* REPRESENTS XTC96 TEST DATA OBTAINED DURING TESTING JAN 97.

TURBOPROP/TURBOSHAFT

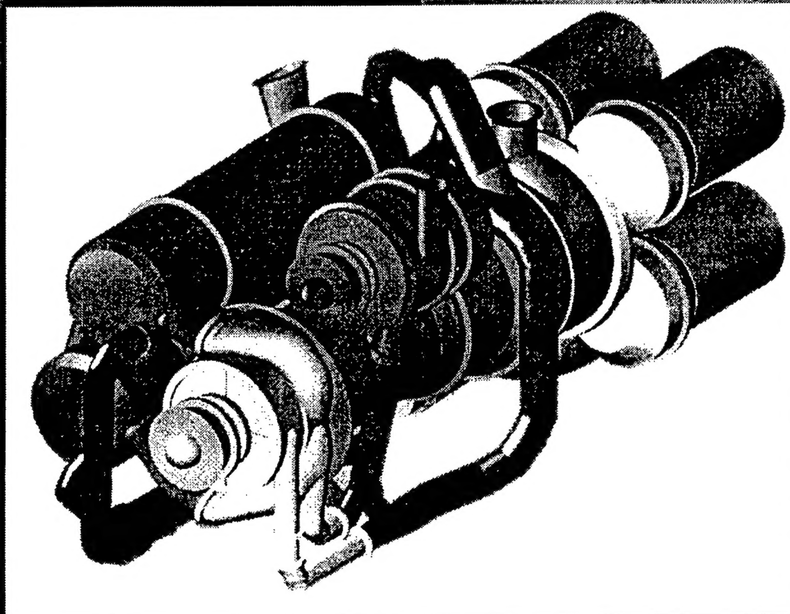
AP.07.00.ANF TRANSPORT/PATROL/HELICOPTER PROPULSION

PAYOFFS, GOALS AND OBJECTIVES



PROPULSION TECHNOLOGY

SEMI CLOSED CYCLE COMPACT TURBINE ENGINE (SC3TE)



- *Fuel efficiency and air usage comparable to best diesel*
- *Far more compact than AGT 1500*

Attributes

- Low SFC over broad power range
  - > 50% fuel savings compared to AGT-1500
- Compact
  - High pressure recuperation means small recuperator
  - Recirculation means small inlet and air handling system

Status

- Overall cycle demo project underway
- Combustion process (recirculation gas) being researched

Vehicle Technology Center

SEMI-CLOSED CYCLE, COMPACT TURBINE ENGINE (SC3TE)

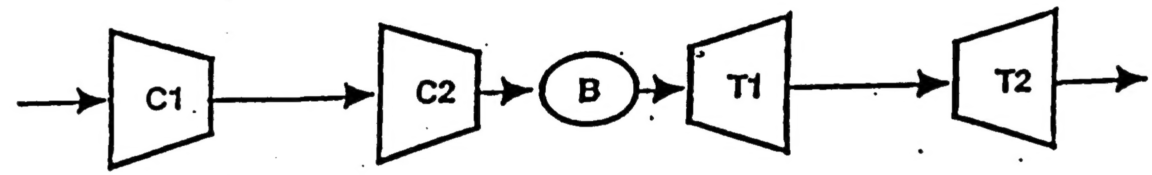
- DESCRIPTION:
  - -CONVENTIONAL TURBOMACHINERY COMPONENTS ARRANGED INTO A UNIQUE, RECUPERATED/INTERCOOLED (RI), SEMI-CLOSED CYCLE

- KEY FEATURES:
  - -RECUPERATION AT HIGH PRESSURE TO SHRINK THE SIZE OF THE HX
  - -VARIABLE FEEDBACK FLOW GIVES AN ADDITIONAL CONTROL PARAMETER TO OPTIMIZE THE CYCLE FOR A PARTICULAR APPLICATION

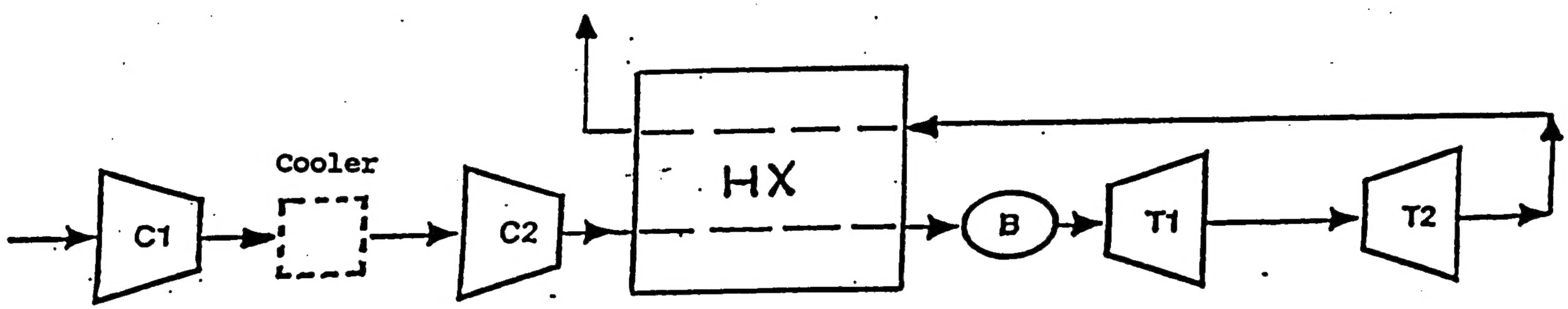
- ADVANTAGES:
  - -FLAT SFC OVER APPROXIMATELY 80% OF THE POWER RANGE
  - -APPROXIMATELY HALF THE WEIGHT AND VOLUME OF CONVENTIONAL R/I ENGINES
  - -VERY HIGH SPECIFIC POWER (HP/UNIT INLET AIRFLOW); APPROXIMATELY 3 TIMES SOA
  - -CONVENTIONAL OPERATING TEMPERATURES (NO MATERIAL BREAKTHROUGHS NEEDED)
  - -INHERENT ATTRIBUTE FOR LOW EMISSIONS
  - -LOWER SIGNATURE DUE TO LOWER AIRFLOW REQUIREMENTS

GAS TURBINE ENGINE CYCLE COMPARISONS
(SIMPLIFIED, SINGLE-SHAFT CONFIGURATIONS)

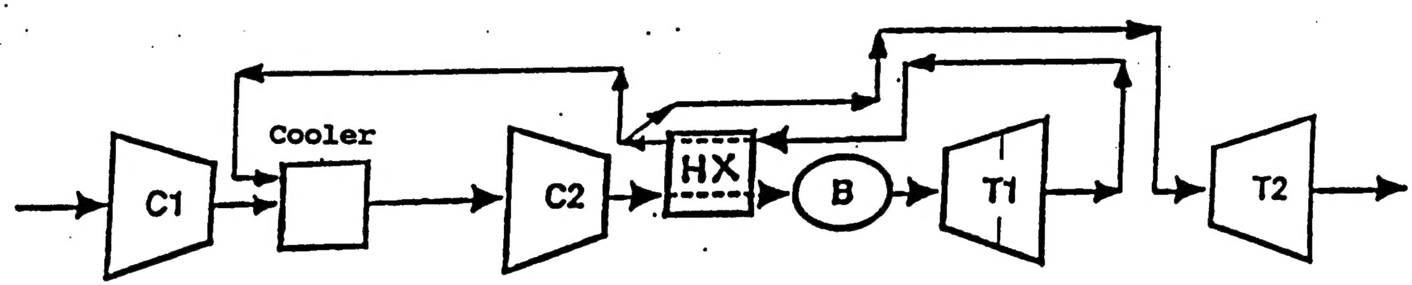
Vehicle Technology Center



CONVENTIONAL, OPEN-LOOP BRAYTON CYCLE



CONVENTIONAL, OPEN-LOOP, RECUPERATED/(INTERCOOLED) CYCLE



SEMI-CLOSED, RECUPERATED/INTERCOOLED CYCLE